Rapport scientifique du Laboratoire Charles Fabry, 2008-2013.

Le Laboratoire Charles Fabry, laboratoire de recherche hébergé par l'Institut d'Optique – Graduate School à Palaiseau, a été évalué par l'Agence d'évaluation de la recherche et de l'enseignement supérieur (AERES) en 2013 sur la base du présent rapport scientifique à cinq ans. Il est rédigé en anglais. Le comité d'évaluation était composé majoritairement de scientifiques non français, dont plusieurs non francophones. Il est mis ici à la disposition des internautes intéressés.

Un autre document disponible fournit la liste de la production scientifique du laboratoire.

Scientific report, Laboratoire Charles Fabry, 2008-2013.

Laboratoire Charles Fabry, the research laboratory at Institut d'Optique – Graduate School in Palaiseau, was evaluated by the French agency for the evaluation of research and higher education (AERES) in 2013 on the basis of this five-year activity report. It is made available here for download by anyone interested.

The laboratory's scientific production is available separately.

CONTENTS

1. Introduction to the research unit

History, localisation, research area

Laboratoire Charles Fabry (LCF) is a joint research unit established as an agreement between Institut d'Optique – Graduate School and CNRS (Centre national de la Recherche scientifique). Such research units are named « unités mixtes de recherche » or UMR. LCF is UMR8501 and has been most recently renewed as such on 1 January 2010. During the AERES evaluation campaign 2013-2014 (called vague E), LCF is under review for possible renewal for the period 1 January 2015 – 31 December 2019. The evaluation will be conducted on the basis of this report, its two companion .xls spreadsheets listing data on finances and personnel, and a set of nine annexes concerning the personnel, the organization chart, various organization rules, and the production in terms of research, interaction with the environment, and research support actions.

This document itself is organized as per the instructions of AERES as a general description in this first section, followed in section 2 by the activity report on the realization of the seven component research groups, then in section 3 with a report on the interaction between research conducted at LCF and higher education tasks fulfilled by its members. Finally, section 4 concludes with perspectives for the next five years.

The reporting period is 1 January 2008 – 30 June 2013.

Institut d'Optique was established around 1920 with the triple mission to deliver teaching in the general field of Optics, conduct research at the forefront of Optics, and interact with the economic sector on optical measurements and more generally on innovation. Its first General Director, Charles Fabry, was at the same time a Physics Professor at the Sorbonne and immediately established a research laboratory following essentially academic criteria (although he would still conduct the more upstream part of his research at his Sorbonne laboratory). When CNRS was first created, in several steps, in the years preceding the Second World War, Institut d'Optique was one of the laboratories receiving support, in particular for the development of optical techniques and instrumentation. Theoretical work and material science research followed shortly thereafter, and when the concept of a "laboratoire associé au CNRS" was first established in 1966, research at Institut d'Optique was immediately granted that status, which was renewed since then and evolved to that of an UMR in 1998. The name of the founding director was added at that time, and in 2006 Institut d'Optique added to its name the subtitle "graduate school" as an indication that it conducts research and offers education at the graduate level – the second and third level of the Bologna system, which in France essentially correspond to the "diplôme d'ingénieur" and master level, and to the doctoral level, respectively. Throughout all these years, support to research has always been provided to LCF by its two founding organizations Institut d'Optique – Graduate School (IOGS) and CNRS, including under the appointment of a fair number of positions of university professors, research scientists, research engineers, technicians, and research support staff. Added resources, both to cover experimental costs and equipment and to cover some of the salaries, was obtained from grants, a tendency that has been increasing in the last few years.

During the reporting period, LCF was mainly located at Palaiseau, at the headquarters building of IOGS, which was built in 2006. Parts of the research activities, including the technical support groups, moved in 2010, when an additional wing was completed. One activity, XUV and Optical Surfaces research, is currently still hosted at the former headquarters building at Orsay, some 4 km from the Palaiseau building, because of lacking funds to build its clean room there. The funds are now available and it is expected to move to Palaiseau late in 2014.

LCF conducts research in Optics in the broad sense. Because of the large diversity of research domains in Optics, it is in fact organized in a number of fairly independent research groups, each covering a well-defined part of Optics research. As explained in the next subsection, during the reporting period, LCF was organized in six, and later seven research groups, and support units providing service to the research groups. The subsequent subsections cover the laboratory organization and daily operation, the financial aspects, and they give an overview of the service support units with LCF.

Scientific policy, organisation

Research groups comprising five to ten permanent staff members (faculty or research faculty) appear to be an appropriate size for productive work, good coordination, and international visibility in the general field cover by LCF. A number of doctoral students roughly equal to the number of permanent staff and one or several post-doctoral fellows are part of the groups as well. Groups consist of scientists who are fully knowledgeable in their field, in particular when they are making decisions collectively, and therefore enjoy a large degree of autonomy in their scientific decisions, including when seeking support from research funding agencies for their research projects and establishing partnerships with academic or industrial research organisations. The scientific policy of LCF is therefore to cover Optics research in a broad sense and organise itself into groups enjoying a strong autonomy to work on identified subjects. Given the variety of subfields in Optics, those groups can only sample part of the whole domain. A necessary condition for that policy to work is to be able to let the organisation into group evolve over time by discussion within the laboratory and by constantly following the trends in Optics as a whole and at its interfaces. As will be seen, the capacity for the laboratory to adapt its group structure has been illustrated during this reviewing period.

The starting date of the current IOGS/CNRS UMR agreement for CNRS is 1 January 2010, two years after the beginning of the reporting period (1 January 2008) to allow for the time needed for reporting to AERES, for the AERES review process, and for the IOGS/CNRS negotiation of the new agreement. At that date, the organization of LCF into groups, was as follows:

- “Atom Optics”. Head: Alain Aspect, with two internal teams
  - *“Quantum Atom Optics and Nanomanipulation of Atoms”, Christof Westbrook*
  - *“Coherent Atom Sources and Atom Interferometry”, Philippe Bouyer*
- “Quantum Optics”, Philippe Grangier
- “Nanophotonics and Electromagnetism”, with three heads: Henri Benisty, Jean-Jacques Greffet, Philippe Lalanne
- “Nonlinear Materials and Applications”, Gilles Pauliat
- “Lasers and Biophotonics”, Patrick Georges, with two internal teams
  - *“Solid State Lasers and Applications”, Patrick Georges*
  - *“Materials, Components and Systems for Biophotonics”, Michael Canva*
- “Optical Systems and Components”, Pierre Chavel, with three internal teams
  - *“XUV Optics”, Franck Delmotte*
  - *“Optical Surfaces”, Raymond Mercier*
  - *“Imaging Systems and Physics of Images”, Jean Taboury.*

In 2009, Antoine Browaeys received an ERC Starting grant. Shortly thereafter, in compliance with the rule that ERC laureates should be supported, in particular to develop autonomy, two internal teams were created inside the “Quantum Optics” group, “Photons”, headed by Philippe Grangier, and “Atoms”, headed by Antoine Browaeys.

In 2010, Christian Chardonnet became the Director of LCF.

In 2011, Philippe Bouyer and Philippe Lalanne left to take part in the creation of the new IOGS/CNRS UMR in Bordeaux.

Also in 2011, scientists who had been working in two of the groups, “Atom Optics” and “Lasers and Biophotonics”, on developing biophotonic instrumentation and methods in cooperation with research groups in medical and biology laboratories, joined forces to create the “Biophotonics” group with Michael Canva as the head. Biophotonics had been identified as a subject for transverse discussions within LCF for several years and the creation of this group was in that respect a fruitful consequence of coordination at the level of the whole laboratory.

In 2012, Jean Taboury and Alain Aspect retired. François Goudail became the head of the “Imaging Systems and Physics of Images” team. Christoph Westbrook, together with Laurent Sanchez-Palencia, a 2012 ERC starting grant recipient, became the heads of the Atom Optics group. Alain Aspect remains active as an emeritus directeur de recherche at CNRS, the Augustin Fresnel Chair Professor at Institut d’Optique and a Professor at Ecole polytechnique.

Early in 2013, Christian Chardonnet left LCF and Pierre Chavel took over as the Director of LCF.

At the end of this reporting period, the organization of LCF into groups, which is the one used in the following sections of this report, is therefore as follows

- “Atom Optics”, with two heads: Christoph Westbrook and Laurent Sanchez Palencia, with three internal teams
  - *“Quantum Atom Optics and Nanomanipulation of Atoms”, Christoph Westbrook*
  - *“Coherent Atom Sources and Atom Interferometry”*

  - *"Theory of quantum Atom Gases", Laurent Sanchez-Palencia*
- "Quantum Optics", Philippe Grangier, with two internal teams
  - *"Photons", Philippe Grangier*
  - *"Atoms", Antoine Browaeys*
- "Nanophotonics and Electromagnetism", with two heads: Henri Benisty and Jean-Jacques Greffet
- "Nonlinear Materials and Applications", Gilles Pauliat
- "Biophotonics", Michael Canva, with three internal teams:
  - *"Single Molecule Biophotonics", Nathalie Westbrook*
  - *"Plasmonics", Michael Canva*
  - *"Imaging Systems", Arnaud Dubois*
- "Lasers", Patrick Georges
- "Optical Systems and Components", Pierre Chavel, with three internal teams
  - "XUV Optics", Franck Delmotte
  - "Optical Surfaces", Raymond Mercier
  - "Imaging Systems and Physics of Images", François Goudail.

Activity profile

As per the AERES instructions, the repartition of activities of the research units and its components is indicated here

Unit / group	Academic research	Interaction with the environment	Support activities	Training through research
Global	40	12	8	40
Atom Optics	40	12	8	40
Quantum Optics	40	12	8	40
Nanophotonics and Electromagnetism	40	12	8	40
Nonlinear Materials and Applications	40	12	8	40
Biophotonics	40	12	8	40
Lasers	40	12	8	40
Optical Systems and Components	40	12	8	40

Note: how to fill the above table was discussed at meetings of the Laboratory Council and the heads of research groups and teams. It was felt that distinguishing between "academic research" and "training through research" was fairly arbitrary, because all our research is conducted by the academic staff in close cooperation with the doctoral students whom they advise. In addition, while some research groups interact more with the academic community at large and some others with industrial research partners, they all contribute to the interaction with the environment, and all serve their share in terms of research support activity. It was therefore felt arbitrary to introduce a distinction between groups at this stage, and estimates of percentages were adopted globally for LCF as a whole.

Organisation and operation of LCF

The LCF staff

This table is provided for the convenience of the reader of the next table and in the following sections.

Professeur des universités	Professor (university faculty position)*
Maître de conférences	Assistant/Associate Professor (university faculty position)*
Directeur de recherche	Research Professor (CNRS position).
Chargé de recherche	Assistant/Associate Research Professor, upper rank (CNRS position).
Ingénieur de recherche	Research engineer (university or CNRS position).
Ingénieur d'étude	Associate research engineer (university or CNRS).
Assistant ingénieur	Assistant research engineer (university or CNRS).
Technicien	Research technician (university or CNRS).
Adjoint technique	adjunct technician (university or CNRS)
Assistant temporaire d'enseignement et de recherche	short term teaching assistant (usually just after PhD)
*	***Except when otherwise indicated, faculty positions at LCF are from Université Paris Sud 11 with teaching duties at Institut d'Optique***

As can be seen from the table below, the staff count at LCF has been fairly stable overall during the reporting period.

Category	January 2001	July 2004	January 2008	**June 2013**
Professeur	3	6	8	**8**
Directeur de recherche	10	10	11	**8**
Maître de conferences	13	13	15	**18**
Chargé de recherche	8	9	12	**12**
Ingénieurs, techniciens (with a permanent position)	52	44	43	**44**
Doctoral students, post-doctoral fellows, visitors	48	42	59	**58**
Total	134	124	148	**148**

In spite of that overall stability, a number of changes occurred. The following colleagues on permanent positions left LCF:

- Alain Aide, assistant ingénieur (CNRS), retired, 2008
- Denis Joyeux, directeur de recherche (CNRS), retired, 2008
- Marie-Françoise Ravet, ingénieur de recherche (CNRS), retired, 2008
- Sophie Guédon, assistante ingénieur (CNRS), moved to another position at CNRS, 2008
- Jean-Michel Desvignes, ingénieur de recherche (CNRS), retired, 2008
- Gisèle Roger, ingénieur d'études (CNRS), retired, 2008
- Nicole Abrial, ingénieur de recherche (CNRS), retired, 2008
- Gérard Roger, ingénieur de recherche (CNRS), retired, 2008
- Michel Alain, ingénieur de recherche (CNRS), retired, 2009
- Danielle Hoffeurt, technicien (CNRS), retired, 2009
- Michel Lamare, ingénieur de recherche (CNRS), retired, 2009
- Pierre Fournet, ingénieur d'études (CNRS), retired, 2009
- Jean-Claude Rodier, ingénieur de recherche (CNRS), retired, 2009
- Carole Arnaud, chargée de recherche (CNRS), left for a different profession, 2009
- Gérald Roosen, directeur de recherche (CNRS), retired 2009
- Françoise Bridou, ingénieur de recherche (CNRS), retired, 2010
- Christiane Vergilino, technicienne (CNRS), retired, 2010
- Marine Laroche, chargée de recherche (CNRS), left for industrial research, 2010
- Cyril Cambournac, chargé de recherche (CNRS), left for another position, 2010
- Jean-Paul Hugonin, maître de conferences (Université Paris 6), retired 2010. He is still active on a voluntary basis.
- Philippe Bouyer, directeur de recherche (CNRS), left for LP2N, the IOGS/CNRS UMR in Bordeaux, 2011
- Philippe Lalanne, directeur de recherche (CNRS), left for LP2N, the IOGS/CNRS UMR in Bordeaux, 2011
- Jean-Yves Clotaire, assistant ingénieur (CNRS), retired, 2011
- Catherine Salou, ingénieur de recherche (CNRS), moved to another laboratory, 2011
- Gilles Colas, ingénieur d'études (CNRS), retired, 2012
- Alain Bellemain, ingénier de recherche (CNRS), retired, 2012
- Alain Aspect, directeur de recherche (CNRS), retired from 2012. He is still active in LCF as an emeritus scientist and professor.
- Jean-Louis Meyzonnette, professeur (IOGS), retired, 2012
- Jean Taboury, professeur (IOGS), retired, 2012

The following colleagues joined research at LCF on permanent positions

- Florence Nogrette, ingénieur de recherche (CNRS), was recruited, 2008
- André Guilbaud, ingénieur d'études (CNRS), joined from another laboratory, 2008
- Jean-Jacques Greffet, professeur (IOGS), joined from Ecole Centrale, 2008
- Marine Laroche, chargée de recherche (CNRS), was recruited, 2008
- François Marquier, maître de conférences (IOGS) joined from Ecole Centrale, 2008
- Jean-Louis Meyzonnette, professeur (IOGS), who formally was not part of LCF, joined in 2009
- Laurence Franchiset, ingénieur d'études (CNRS), was recruited, 2009
- Alexei Ourjoumtsev, chargé de recherche (IOGS), was recruited, 2009
- Isabelle Soury, ingénieur d'études (IOGS), was recruited, 2008
- Mickaël Ribeiro-Pereira, adjoint technique (IOGS), was recruited, 2009

- Gilbert Lucas, ingénieur de recherche (CNRS), was recruited, 2009. He was formerly an ingénieur d'études in another laboratory
- Sylvie Janicot, ingénieur d'études (CNRS), joined from another laboratory, 2010
- Nathalie François, technicienne (CNRS), joined from another laboratory, 2010
- Jocelyne le Guen, adjoint technique (IOGS), was recruited, 2010
- Evgueni Meltchakov, ingénieur de recherche (IOGS), was recruited, 2010
- David Clément, maître de conférences (IOGS), was recruited with a CNRS supported chair, 2010
- Anne-Lyse Coutrot, ingénieur de recherche (CNRS), was recruited, 2011
- Philippe Ben-Abdallah, directeur de recherche (CNRS), joined from another laboratory, 2011
- Kenza Cherkaoui, ingénieur de recherche (IOGS), was recruited, 2011
- Ioana Doyen-Moldovan, ingénieur de recherche (CNRS), was recruited, 2012
- Michel Parise, technicien (CNRS), joined from another laboratory, 2012
- Carmen Zèques, ingénieur d'études (CNRS), was recruited, 2012
- Matthieu Boffety, maître de conférences (IOGS), was recruited, 2012
- Caroline Kulczar, professeur (IOGS), was recruited, 2012
- Henri-François Raynaud, maître de conferences (Université Paris 13), joined for his research activity, 2012
- Thierry Lahaye, chargé de recherche (CNRS), joined from another laboratory, 2012
- Fabrice Cartier, adjoint technique (IOGS), was recruited, 2012
- Marc Cheneau, chargé de recherche (CNRS), was recruited, 2013.

In addition, Christophe Sauvan, chargé de recherche (CNRS), joined LP2N for a short period and moved back to LCF. Nathalie Boulay-Laurent, ingénieur de recherche (CNRS), was recruited in 2012 and left after a few months for another position at CNRS.

Among the 12 new faculty and research faculty members who joined

- 6 came from other laboratories (with the same rank)
- 4 were recruited and had never worked at LCF before
- 2 were former doctoral students at LCF who were recruited after a post-doctoral period abroad.

Financial data

LCF is supported to a large extent by the two partner institutions that created it as an UMR, IOGS and CNRS. Both provide permanent salaries at comparable levels to a total of some 6 million euros per year. IOGS hosts LCF on its premises and provides the infrastructure, maintenance and administration. However, only part of the infrastructure, maintenance and administration costs, which together amount to nearly 1 million euros, are born by IOGS and overhead has to be charged from the contracts and grants secured by the research groups.

All scientific expenses and non-permanent staff salaries (mostly doctoral students and post-doctoral fellows) must be obtained from research contracts and grants. The annual flow of contracts and grants is on the order of 4 million euros and has been fairly stable during the reporting period. The main sources of contracts and grants are

- The EU Framework Programme, for 29%
- The French national Research Agency ANR, for 23%

Other significant sources of funding include Délégation générale pour l'Armement (a defense related agency), CNES (the national Center for Space Research), the Ministry of higher Education and Research for various kinds of doctoral student salaries, and the territorial governments of Région Ile de France and Département de l'Essonne. Furthermore, in recent years, there has been a strong trend by the government to introduce new sources of contract funding under so-called "réseaux thématiques de recherché avancée" (RTRA) and "initiative d'excellence", which include "laboratoires d'excellence" (Labex) and "équipements d'excellence" (Equipex). Those funds are mostly made available to laboratories after proposal evaluation by suitable committees through a "fédération de cooperation scientifique" where all research and higher education institutions active on a given territory are present. One intention of those measures is to increase collaborations with local research partners. LCF has benefited significantly from the RTRA "Triangle de la Physique" and more recently from Labex PALM (Physique: Atomes, Lumière, Molécules) and Equipex (MORPHOSCOPE, on XUV imaging for biological applications, ATTOLAB for attosecond science, and CILEX – "Centre interdisciplinaire Lumière extreme").

Most of those sources of funding are made available to consortia of laboratories. Research laboratories from industry are allowed and often encouraged to participate and can receive funds. LCF has collaborated in such consortia with over 30 industrial institutions during the reporting period, and about 15% of its contract funds were obtained within consortia where industry was present. Industry itself funds some 5% of the total contract budget.

Life at LCF

Seminars

As has been said, scientific activity at LCF is organized into fairly independent research groups. Nevertheless, some scientific activities are common to LCF as a whole. Seminars are typically organized most of the Thursdays after lunch time: speakers include prominent visitors, but also the LCF doctoral students, who are asked to present at least one seminar during their thesis preparation, typically at mid time. The Thursday after lunch agenda is always fairly busy and typically cannot accommodate all presentation by visiting colleagues.

The IOGS facilities at Palaiseau are appropriate to host workshops and small scientific meetings. In many cases, those are organized by LCF scientists. Also, the recently established Student Chapter on Optics in Paris (SCOP), supported by EOS, SFO, OSA and SPIE, organizes some of its events at Institut d'Optique. An OSA Chapter IONS meeting was hosted in 2011.

Leadership, internal committees and assemblies

Two advisory committees have been established to follow the life of the laboratory and meet on a regular basis:

- The laboratory council (conseil de laboratoire), consisting of a combination of elected staff members from the different categories of personnel and members appointed by the director. It has a statutory role and follow rules that are attached in appendix 5. It meets typically five to six times a year to discuss every aspect of the laboratory life and is legally requested to examine the laboratory budget and the initial and final phases of the recruitments ("profil de poste", "titularisation").
- The meeting of the heads of groups and teams has been established informally in 2010 as a body which meets four or five times per year and discuss scientific issues, open positions, investments, major new contracts and changes in the scientific organization of the laboratory and its environment.

Technical and administrative support units

While research work is typically done in the research groups, an essential and much appreciated part of the work is research support work done by support units, which are all on high demand from the research groups. They are listed here along with their staff members as of June 2012. Two categories will be distinguished:

- research support units internal to the laboratory, which are all devoted to technical and scientific activities,
- research support units that are common to the whole IOGS, including its two UMR, LCF and LP2N (Bordeaux), which therefore devote part of their time to LCF and part of their time to IOGS as a whole or to LP2N. Those offer typically management functions, but also computer services, documentation, communication, and maintenance.

Only staff members on permanent positions as of 30 June 2013 are listed.

Research support units internal to the laboratory

For many years already, engineering support services in mechanical design, mechanics, optical system design, polishing and optical metrology have been organised centrally at LCF. Until recently, a number of engineers and technicians were appointed to working in the research groups. That mode of operation has proved effective, with the exception that it does not grant to each group a perfectly fair part of the engineering support resources available. The vast majority of the latter engineers and technicians, however, have retired in the last few years. There is therefore both a need and an opportunity to organise engineering support within LCF as a common department, ideally under a appointed coordinator. Instrumentation, nanotechnology, electronics, and scientific computing were therefore established as research support units working for the whole laboratory Ideally, engineers and technicians should be assigned tasks within a given group for periods of time ranging from weeks to years, and spend the appropriate fraction of their time with that group, but not be formally members of that group. The right hand column of the organisational chart (appendix 4) reflects the current situation. In the group reports, engineering support service members who have spent a large fraction of their time in the particular group are mentioned.

Nanofabrication technology

- Anne-Lyse Coutrot, ingénieur de recherche, CNRS

- Buntha Ea-Kim, ingénieur d'études, IOGS
- Arnaud Jérôme, assistant-ingénieur, CNRS

LCF has access to four facilities with together quite a considerable variety of equipment:

- the extreme UV multilayer deposition activity has been equipped for nearly fifteen years with good proper facilities in a small dedicated clean room, maintained by one technician of the XUV team. The facility is still at the old building of IOGS at bâtiment 503 on the Orsay campus but is expected to be moved to Palaiseau late in 2014.
- The TRT – Ecole Polytechnique – IOGS joint technology facility has been in operation for three years now. The main contribution in equipment of IOGS as a founding partner is a NanoBeam ® e-beam lithography facility.
- National facilities exist both at Laboratoire de Photonique et Nanostructures (LPN), Marcoussis – some 10 km from LCF, and at Minerve, a facility on the Orsay campus of Université Paris-Sud 11 that rests upon the skills available at Institut d'Electronique Fondamentale.

With three engineers currently active full time on nanofabrication technology, good service is available to optimally use and maintain the high technology equipment available. Faculty members and doctoral students who would like to use the facilities receive proper training. However, at this stage, a full time faculty member devoting his research to technological processes is still missing.

Optic shop

- Christian Beurthe, technicien, CNRS

Staff has decreased from three to one member. Fortunately recruitment late in 2013 is expected, but still, the size of the team will remain critical. The LCF optical shop has been active since the beginning of IOGS many decades ago. As commercial offer for off-the-shelf components developed and technical staff at IOGS decreased, it evolved from a general production facility to a specialized polishing unit consisting of three glass polishers. In addition to occasional counselling to the groups, these colleagues provide mostly high-end optical shop services. Typically, production includes plane and spherical surfaces of size up to 120 mm and very high shape and surface accuracy. The devices fabricated by the optical shop at LCF for selected projects such as a Fourier Transform spectrometer operating in the wavelength range of 50 to 140 nm would not be available from the international market at costs that LCF could afford (even on grants) and those projects could not possibly be envisaged.

Mechanical design and fabrication

- Person in charge: André Guilbaud, ingénieur d'études, CNRS
- Michel Parise, technicien, CNRS
- Patrick Roth, adjoint technique, IOGS

Three engineers and technicians offer fast access to mechanical services for small operations, draftsman skills to design complex instruments, a centralized shop for mechanical fabrication, and services to optimally assign the mechanical fabrication tasks to internal production and to subcontracting. Approximately 70% of the fabrication is subcontracted.

Electronics

- Frédéric Moron, technicien, CNRS, currently mostly with group Optique Atomique
- André Villing, ingénieur de recherche, CNRS, currently mostly with group Optique Atomique

While sharing some resources in equipment and consumables, the electronics engineers and technicians are mostly assigned to specific groups where they spend most of their time, but they are available to the requests from other groups for part of their time. They deserve to be recognized for some remarkable specific achievements in instrumentation, which are listed in the group reports.

Instrumentation

- Ioana Doyen-Moldovan, ingénieur de recherche, CNRS (lasers, design of new instruments)
- Sylvie Janicot, ingénieur d'études, CNRS (lasers)
- Florence Nogrette, ingénieur de recherche, CNRS (vacuum, interferometry, opto-mechanics)

Instrumentation is the most recently established technical research support unit. While the help of those engineers is critically important in support to the projects of the various group, a smooth way to assign the instrumentation engineers to the groups for given periods of time will need to be established. Ioana Doyen-Modovan is also part-time in charge of industrial partnership contacts.

Optical design and modelling

- Mondher Besbes, ingénieur de recherche, CNRS

Mondher Besbes contributes research on algorithms in conjunction with several groups but mostly in nanophotonics. He is also the coordinator of access to computing clusters and an advisor for computing methods to all groups.

Research support units common to the whole IOGS

Annie Montagnac, ingénieur de recherche, CNRS, heads globally those research support units.

Financial affairs, accounting and personnel:

- Abdelaaziz Aboulahyane, technicien, CNRS
- Jocelyne Armand, assistant-ingénieur, IOGS
- Christine Avignon-Vérité, assistant-ingénieur, IOGS
- Nathalie Baudry, technicienne, CNRS
- Ghislaine Canale, adjoint technique, IOGS
- Audrey Chedorge, assistant-ingénieur, IOGS
- Nicole Estèves-Mangeon, adjoint technique, CNRS
- Nathalie François, technicienne, CNRS
- Isabelle Soury, ingénieur d'études, CNRS
- Ghislaine Théneau, agent technique, IOGS
- Carmen Zèques, ingénieur d'études, CNRS

Service intérieur:

- Marie-Hélène Bellart, adjointe technique, IOGS
- Christine Bruneau, technicienne, IOGS
- Jean-Luc Cadoré, assistant ingénieur, CNRS
- Fabrice Cartier, adjoint technique, IOGS
- Jocelyne le Guen-Moizan, adjointe technique, IOGS
- Graça Martins, technicienne, IOGS
- Jacky Robin, ingénieur d'études, IOGS, head of safety and maintenance

Library:

- Head: Marie-Laure Edwards, assistant-ingénieur, CNRS
- Fatima Pereira, agent technique, IOGS

Computer services

- Head: Gilbert Lucas, ingénieur de recherche, CNRS
- Laurent Leclercq, assistant-ingénieur, CNRS
- Mickaël Ribeiro-Pereira, adjoint technique, IOGS

Communication

- Kenza Cherkaoui, ingénieur de recherche, IOGS, head of communication
- Laurence Franchiset, assistante ingénieur, CNRS

Executive summary

An executive summary listing what we, the members of LCF, consider to be our most noteworthy achievements during the reporting period is appended as appendix 1 (document S2-1-3-UR-presentation-synthetique_LCF_vf2.pdf).

2. Production

The following pages list the activity reports of the seven research groups, their scientific achievements, their contribution to the reputation and academic activity, their interaction with the social, economic and cultural environment, including a mention of their research perspectives for the years to come. Each report consists of six pages preceded by the list of the members of the group during the reporting period.

After those separate sub-chapters devoted to the seven groups, parts 3 and 4 of the report, about the interaction with education activities and about the research strategy, conclude this document.

ATOM OPTICS

OPTIQUE ATOMIQUE

ATOM OPTICS GROUP MEMBERS

Responsables:

WESTBROOK Christoph, Directeur de Recherche, CNRS
SANCHEZ-PALENCIA Laurent, Chargé de Recherche, CNRS

Faculty and Research Faculty holding permanent positions

ASPECT Alain	Directeur de Recherche CNRS (emeritus since Sept. 2012)
BOIRON Denis	Maître de conférences IOGS/U. Paris-Sud (Professeur, 2013)
BOUCHOULE Isabelle	Chargé de Recherche CNRS
BOUYER Philippe	Directeur de Recherche CNRS (moved to LP2N, 2011)
BOURDEL Thomas	Chargé de Recherche CNRS
CLEMENT David	Maître de Conférences IOGS/U. Paris-Sud (arrived 2010)
CHENEAU Marc	Chargé de Recherche CNRS (arrived 2013)
JOSSE Vincent	Maître de Conférences IOGS/U. Paris-Sud

Doctoral students, graduated

NAME	**Funding**	**Date of defense**	**Current position**
VAROQUAUX Gael	AMN	Jan-08	CDI INRIA Saclay
CLÉMENT Jean-Francois	Doctoral School	Nov-08	MC Lille
KRACHMALNICOFF Valentina	Doctoral School	Jun-09	CR2 ESPCI Paris
BRANTUT Jean-Philippe	DGA	Nov-09	post-doc Zurich
LUGAN Pierre	AMX	Jan-10	postdoc Lausanne
EL AMILI Karim	Doctoral School	Jan-10	post doc Nantes
BILLY Juliette	DGA	Feb-10	MC Toulouse
BERNARD Alain	AMN	Nov-10	Prof cl. préparatoires Meaux
JASKULA Jean-Christophe	Doctoral School	Dec-10	post doc Cambridge, MA
ROBERT DE ST-VINCENT Martin	AMN	Dec-10	MC Paris 13 Villetaneuse
BERNON Simon	AMX	Apr 11	CDI CEA Saclay
ARMIJO Julien	Doctoral School	May-11	post doc Santiago
GEIGER Rémi	CNES/RTRA	Nov-11	MC Paris-6 SYRTE Paris
BONNEAU Marie	Doctoral School	Dec-11	post doc in the OA group, then Florence
VANDERBRUGGEN Thomas	DGA	Apr-12	Post doc Barcelona
MENORET Vincent	DGA	Sep 12	CDI µQuans Bordeaux
ALLARD Baptiste	DGA	Oct 12	Post doc Basel
JENDRZEJEWSKI Fred	CNRS	Nov 12	post doc College Park, MD
JACQMIN Thibaut	AMN	Nov 12	post doc Marcoussis
PLISSON Thomas	AMX	Nov 12	CDI CEA Bruyeres le Chatel
PIRAUD Marie	AMN	Dec 12	post doc in the OA group, then Munich

Current doctoral students

RUAUDEL Josselin	DGA (2010-)
KOHLHAAS Ralf	Doctoral School (2010-)
BERRADA Tarik	Autriche (cotutelle) (2010-)
HOENDERVANGER Lynn	IFRAF (2011-)
MUELLER Kilian	ERC (2011-)
SALOMON Guillaume	DGA/RTRA (2011-)
LOPES Raphael	Portugal (2011-)
LELLOUCH Samuel	AMX (2011-)
FANG Bess	Doctoral School (2011-)
FOUCHÉ Lauriane	DGA (2012-)
RICHARD Jéremie	DGA (2012-)
IMANALIEV Almazbek	IOGS ERC (2012-)
BOERIS Guilhem	AMX (2012-)

The group benefitted considerably from the engineering support staff, and in particular Frédéric Moron and André Villing, electronic engineers.

Visiting scientists and post-doctoral fellows

BATTELIER Baptiste	ICE
BERTOLDI Andrea	BIARO
CARLEO Guissepe	Theory
CHEINET Patrick	Anderson Localization
DAO Tung-Lam	Theory
FANG Yami	Atoms in optical lattices
GARRIDO ALZAR Carlos	Atom Chips
GLEYZES Sébastian	Atom Chips
LEUNG Vanessa	Helium
LIM Lih-King	Theory
NYMAN Rob	Disordered 2D Gases
PARTRIDGE Guthrie	Helium
PEZZE Luca	Theory
STERN Guillaume	ICE
WANG Pengjun	Disordered 2D Gases

1. SCIENTIFIC REPORT

The Atom Optics group was started in 1991 by Alain Aspect with the idea of developing analogies between "traditional" optics and the manipulation of atoms using electromagnetic fields. This endeavor had been stimulated in particular by the advent of atom cooling techniques which enabled the realization of long coherence lengths for the spatial degrees of freedom of an atomic ensemble. Many major breakthroughs in the 1990's concerned experiments exploiting the wave nature of the atoms. The demonstration of Bose-Einstein condensation in 1995 provided in some sense the ultimate coherent atom source and researchers throughout the world participated in the study of coherent effects: measurements of interference and coherence properties, observations of wave mixing etc. After the year 2000, two new directions have emerged in the field, which are now at the center of our activities. On the one hand, we can now study what might be called "quantum atom optics", a field in which quantum fluctuations and entanglement play an essential role. On the other hand, we have seen a flowering of another application of ultracold atoms, the development of analogies to condensed-matter physics, especially those involving many-body, low temperature and disorder physics.

In the past 5 years, the Atom Optics group has been developing experimental and theoretical activities in both these areas. Broadly speaking, these activities are logical extensions of the work described in the activity report in 2008. As we describe below, the specific subjects we have been working on have slightly evolved, in part due to some changes in the personnel of the group.

As a "directeur de recherche émérite" since 2012, Alain Aspect is still an active member of the group and a chair holder at Ecole polytechnique and at Institut d'Optique. As of January 2011, Philippe Bouyer, one of the senior members of the group, has become the director of the LP2N, the new lab of Institut d'Optique in Bordeaux. Philippe was involved in, and indeed initiated several of the activities in the group. Some of these activities, especially those associated with the study of disordered potentials, involve permanent researchers of the LCF, and the setups continue to operate in Palaiseau with the continued collaboration of P. Bouyer. Other activities especially those related to interferometry, the BIARO and ICE experiments, have moved to the LP2N. In other developments, the biophysics project (N. Westbrook and K. Perronet) left the group and joined the newly created Biophotonics group of the LCF in September 2011. Their activities are described elsewhere. The group has recruited two new researchers between 2008 and 2013, David Clément and Marc Cheneau. David Clément has initiated a new activity on optical lattices. Marc Cheneau, who joined the group in January 2013 has joined the quantum optics with metastable helium project.

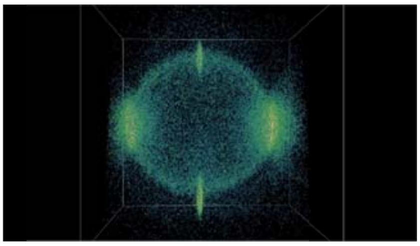
The theory team, created in 2006, has further developed and established itself as an autonomous activity. It has reached a reasonable size (1 permanent, 2 post-docs, 3 PhDs) and has received a significant impetus via an ERC-Starting grant. Part of its activity is in collaboration with experiments and the close contact between experimentalists and theorists within the same group is highly beneficial. In addition, the staffing of the theoretical team has allowed the development of complementary approaches, combining analytics and large-scale numerics. We have been able to recruit 3 post-docs with backgrounds in condensed matter, which has been a real asset for bridging the gap between atomic and condensed-matter physics. An example is the development of a new line of research using Quantum Monte Carlo simulations.

The large size of the group and its relatively narrow scientific scope has many benefits. An invaluable exchange of ideas takes place in weekly group meeting as well as during informal discussions. It is also essential that we share experimental knowhow and equipment. This synergy is increased by the presence of an electronics shop, staffed by Fréderic Moron and André Villing, which is able to design and build many devices which are not available commercially. Finally the group tends, whenever possible, to pool its funding, or at least to coordinate expenditures. This goes both for equipment and for personnel. This organization often allows us to quickly launch new operations, which might otherwise require a considerable time to acquire outside funding.

A. Quantum Atom Optics

A.1 Quantum atom optics with metastable helium

Metastable helium (helium atoms in the 2^3S_1 state, vacuum lifetime 8000 s, hereafter denoted He*) is metastable against collisional loss processes (especially Penning ionization) when fully polarized. In this situation the behavior of a condensed gas of He* closely resembles that of other species such as Rb. Its chief interest lies in the fact that its metastable character lends it to detection by purely electronic means such as by micro-channel plates (MCP's). These MCP's coupled to position sensitive anodes, permit the detection of individual atoms in three dimensions. The counting capability provides an excellent tool for quantum atom optics: quantum correlations and atom statistics are accessible in this system, and such measurements form the basis of the scientific results. An example of the capabilities of the detector is in the figure below. It shows the reconstruction of an atomic 4 wave mixing process, in which 3 condensates collide and produce a fourth one.



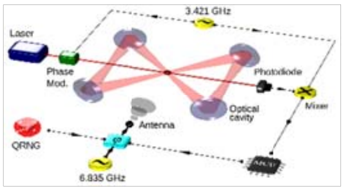
3 dimensional image of a cloud of helium atoms falling on a position sensitive MCP detector. Each dot represents a single atom. The image shows a 4 wave mixing process in which 3 condensates (right, left and bottom) collide to produce a fourth one (top). The image also shows a spherical halo of scattered atoms.

In addition to the 4 condensates in the figure, there is also a spherical halo of atoms resulting from spontaneous scattering in random directions. Because of its non-linear nature, 4 wave mixing is a process which can produce non-classical states of the de Brogile wave field – especially in the modes which are populated by spontaneous scattering. In the experiments, the group has demonstrated that the atoms on the halo are correlated with a partner having the opposite momentum, and that their number difference is sub-Poissonian (Jaskula PRL 2010). We have shown that this "number squeezing" corresponds to a violation of the classical Cauchy-Schwartz inequality. In addition, the team has been exploring other methods of *atom pair production*. It is possible to use an optical lattice to reduce the available modes for the spontaneous scattering events, and thus achieve a large and tunable population in the paired modes. Future plans include the demonstration of the entanglement of these modes. Finally the team has been investigating the production of paired excitations in the phonon regime via the parametric downconversion of phonons (Jaskula PRL 2012). In an alternative interpretation of the effect, one can consider it the acoustic analog of the "dynamical Casimir effect"[1], an effect well known but difficult to observe for the electromagnetic field.

A.2 The The "BIARo" Experiment

The BIARO (*Condensation de Bose-Einstein et Interférométrie Atomique dans un Résonateur Optique*) project was initiated in 2008, with the goal of producing and trapping a Bose-Einstein condensate in a high finesse optical resonator and at the same time using the cavity to enhance the interaction between the atoms and an interrogation beam. In this configuration, quantum non-demolition measurements and spin squeezing can be performed with condensates. A long term goal is to develop the technology to enhance signal to noise in atom interferometry experiments.

Trapped ensembles are dispersively probed using optical heterodyne detection, which can nondestructively measure the population difference between the two hyperfine states, or control a coherent superposition state of the ensemble. Combining these two capabilities in a feedback system, the team has demonstrated that an initial state has been protected against different kinds of random noise, implemented as collective rotations of the atomic spins (Vanderbruggen PRL 2013). This technique can be used for the operation of atomic interferometers beyond the standard Ramsey scheme, opening the way towards improved atomic sensors. In a related development, the team is now using such "weak measurements" to operate an atomic clock beyond the interrogation limit set by the local oscillator: it is possible to interrogate phase drift between the local oscillator and the atomic reference, and then to apply a correction and continue the measurement.



Schematic diagram of the BIARO experiment showing the resonant cavity in a "bowtie" geometry to trap the atoms. A phase modulated laser beam passes through the trapped sample and is detected using an rf heterodyne technique. A quantum random number generator (QRNG) is used to simulate various types of phase noise in such a system, and a feedback loop is able to correct noise induced errors.

A.3 The ICE Experiment

The I.C.E. experiment (*Interférometrie atomique à sources Cohérentes pour l'Espace* - Coherent atom interferometry for space applications) is a compact and transportable atom interferometer, designed to test the Universality of Free-Fall in a plane carrying out parabolic flights. It is a collaboration between three French labs : Institut d'Optique, LNE-SYRTE and ONERA. The project is largely funded by CNES and ESA.

The experimental apparatus has been specifically designed to withstand vibrations and temperature fluctuations in the plane. In March 2010, we used a hybrid sensor, made of the atom interferometer and a mechanical accelerometer to measure the plane's acceleration, both at 1g and in 0g. The team was able to measure accelerations 300 times lower than the plane's acceleration level. In May 2011 they flew with a new version of the laser system, enabling simultaneous cooling of Rb and K atoms. They obtained the first dual-species Magneto-Optical Trap

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[1] I. Carusotto *et al.*, Eur. Phys. J. D. 56, 391 (2010).

(MOT) in microgravity. The cooling lasers are locked on a self-referenced optical frequency comb which acts as a common frequency reference, and which was successfully tested in flight. In September 2011, the experiment was moved to Bordeaux to integrate the new laboratory LP2N.

A.4 Other atom optics experiments

Other parts of the group have also been, at times, interested in work which falls under the heading of atom optics. In particular, the Rb-Kr experiment demonstrated a *quantum trampoline* for atoms. The idea was placing atoms in a vertical, pulsed optical standing wave and to levitate them by repetitive Bragg scattering. The goal was to increase the possible interrogation time in an atomic interferometer. After demonstration of the principle in 2010, the research program of this team has shifted to the study of 2 dimensional gases in disordered potentials, as will be described below.

The atom chip team has also been involved in atom optics research. In attempt to integrate optical functionalities with electrical ones on the same chip, they initiated a project to fabricate a wave guide structure made of GaAs on a chip along with the wires necessary for trapping atoms. In collaboration with the researchers at the LPN Marcoussis, the team was able to realize an optical cavity using a ridge waveguide with a finesse of order 100. To make the light in this cavity interact with trapped atoms a ~ 2 µm wide air-gap was cut in the guide through which atoms could be guided. A careful study was made on the optimization of the size of the gap as well as the other cavity parameters. The technical realization of this gap has proven prohibitively difficult however and the project was terminated in 2010.

In a separate project, the group has been participating in an ANR contract (CATS) coordinated by Thales Research lab. The goal is to produce an accelerometer using atoms on an atom chip. The CATS project is a collaboration between Thales, IOGS, and two laboratories in Paris. The atom chip group has been participating by carrying out tests of new chip materials such as SiC. The team has also been participating in the theoretical modeling of effects such as trap anharmonicity and different beam splitter designs in order to guide the design of a chip which will be used in a laboratory at Thales.

B. Experiments at the Interface with Condensed Matter physics

B.1 Studies of 1 dimensional gases

The statistical physics of one dimensional (1D) systems is a fascinating subject with a long history. The subject is unusual in that exact solutions of the many body problem exist in certain cases, leading to many insights not available in other systems. At the LCF we have been studying 1D gases using atom chips. Atom chips consist of substrates on which electrical wires have been lithographically deposited. Currents in the chip produce magnetic fields which can trap and manipulate atoms, Rb in our case. The trapping potentials are typically highly elongated, having a very strong confinement along two axes and a much weaker confinement in the third. It is possible to make the transverse confinement so strong that the transverse degrees of freedom are frozen and thus a good approximation to a 1D gas is achieved. The 1D nature of the sample, as well as its compactness, which enables a very stable imaging system, means that atom chips lend themselves to low noise, high resolution imaging.

Our principal scientific results have centered on studies of the fluctuation properties of the images of the gases. Density fluctuations in the gas are sensitive probes of the 1 dimensional phase diagrams of these gases, which tend to exhibit smooth crossover behavior rather than abrupt phase transitions. We have investigated the dimensional crossover between the one-dimensional and the three dimensional physics, showing that, at high temperature, the (quasi-)condensation is triggered by transverse condensation and is quite sharp, in contrast the smooth behavior observed in purely 1D gases. We have also investigated the third moment of density fluctuations, showing a skewness related to the presence of three-body interactions (Armijo PRL 2010). With the strong confinement possible in our latest generation of chips we have been able to achieve the "fermionized" regime in which the fluctuations are strongly suppressed and resemble those of a Fermi gas (Jacqmin PRL 2011).

The team has also performed the first measurements of the momentum distribution of purely 1D Bose gases. No exact results are available for the momentum distribution of 1D Bose gases and so comparisons are made with quantum Monte Carlo calculations due to Tomaso Roscilde from ENS Lyon. We also made some theoretical investigations of the validity of the classical field approach in a 1D gas via the study of correlation properties (Bouchoule PRA 2012).

B.2 Studies of disorder in 2 dimensional gases

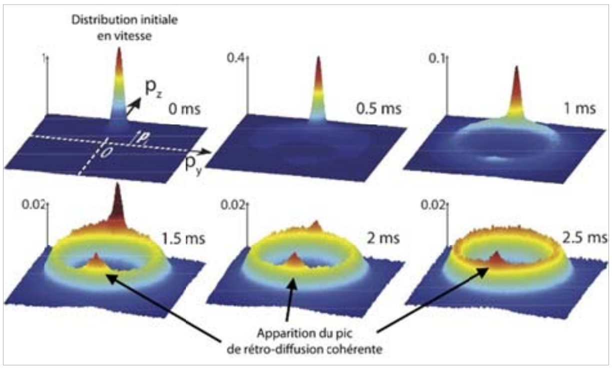
The interplay between interactions, statistics and disorder in 2 dimensions is an open problem and has strong links to many condensed matter systems including those exhibiting superconductor-insulator transitions. Our group has pioneered this field with a series of studies. First, we have studied the diffusive behavior of an essentially non interacting 2D gas in the presence disorder. In particular, in a project carried out in collaboration with the theory team, we were able to reconstruct the diffusion coefficients as a function of energy (Robert de St. Vincent PRL 2010). We then turned our attention to the physics of superfluidity in 2D. First, without disorder, we use a very long time of flight technique to study the coherence properties close to the 2D superfluid transition. This precise study and comparison with Monte-Carlo simulations complemented previous publications for the characterization of 2D Bose gases properties. For us, this work was a starting point for a quantitative study of the influence of disorder on superfluidity in 2D (Allard PRA 2012). The work has provided data in an unexplored region where the physics is only partially understood. Our experiment has stimulated further theoretical studies on this subject which have also been recently published (Bourdel PRA 2012).

B.3 Anderson localization in 3 dimensions

Over the past 5 years, our team has continued its pioneering research on the study of ultracold atoms in presence of disorder. The experimental challenge is to build quantum simulators in order to address fundamental issues on disordered systems, with a special emphasis on the study of Anderson localization.

In 2008 we succeeded in directly observing the genuine Anderson localization of matter waves in presence of a laser speckle potential and in a one-dimensional geometry (Billy, Nature 2008). The experimental results were in remarkably good agreement with the theoretical predictions of the group's theory team, opening the way towards meeting the challenge of studying Anderson localization in higher dimensions. In particular, the comprehensive study of the phase transition that occurs in 3D between localized and diffusive, extended states remains a formidable task for experiments, numerics and theory.

After the move to the new building in Palaiseau (june 2008), the team designed a new experimental apparatus, dedicated to the study of Anderson localization in 3D. The first experimental evidence of 3D Anderson localization with ultracold atoms was observed in 2011 (Jendrzejewski, Nature Phys 2012), simultaneously with the group of B. deMarco at Urbana-Champain. Despite this success however, this work has revealed a fundamental bottleneck. The ultimate goal is to study the 3D phase transition between localized and diffusive states, but our method of introducing a condensate, even at zero temperature, into a disordered potential, results an energy broadening which precludes making measurements close to the phase transition. Because of this difficulty, the development of alternative schemes and signatures is highly desirable. Consequently, the team has turned its attention to coherent backscattering (*i.e.* weak localization) and made the first direct observation this effect with ultracold atoms. The observation provides the first direct proof of phase coherence in disordered quantum gases. The figure below shows an example of the experimental data (Jendrzejewski, PRL 2012).



Coherent backscattering of de Broglie waves. Images in momentum space of a cloud of atoms scattering from a speckle potential. The images show successive times after the initial preparation of the atoms in a well-defined, non-zero momentum p_z (upper left image). Gradually, a circular distribution centered at zero momentum develops. Beginning in the frame at 1 ms one observes the appearance of a peak in the backward direction which persists even after the initial peak is gone.

B.4 Atoms in optical lattices: strongly correlated systems

With the arrival of David CLEMENT in the Atom Optics group in September 2010, a new experimental activity has started. Building on the knowledge of our group to manipulate and detect metastable helium atoms at the single atom level, this activity will be centered on the study of atom-atom correlations in many-body quantum states. The intent is to exploit our ability to measure atom correlations to the study many body physics. In the summer of 2011 construction of the apparatus began. Currently the team has built the vacuum apparatus, installed the necessary laser cooling systems and realized a magneto-optical trap. There have also been some parallel technical advances. A study of the behavior of micro-channel plates was performed and published recently, and a new electronic scheme to lock the laser onto the atomic transition in an atomic discharge has also been developed and published (Moron, Rev. Sci. Inst. 2012).

C. Theory

The field of disordered ultracold gases has now reached a significant degree of maturity. Disordered quantum gases have now taken their full place beside traditional condensed-matter physics, as recognized by the large number of dedicated sessions in most general conferences on disorder physics in the past years. The Atom Optics group has actively contributed to the emergence of the field both at the experimental and theoretical levels. Currently the activity of the theory team is mainly devoted to this topic. Our activities can be understood in the context of a recent published overview of the future of the field (Sanchez-Palencia and Lewenstein, Nat. Phys. 2010). On one hand, we have been proposing and analyzing new experiments to address long-standing issues in the field of disordered systems. On the other hand, we study novel effects beyond standard models of condensed-matter theory.

C.1 Anderson localization: from 1D to 3D, anisotropy and trapping

A large part of our activity has been devoted to the study of quantum transport and Anderson localization in optical disorder. Our early work showed the role of long-range correlations in one-dimensional speckle potentials, leading to so-called effective mobility edges (Sanchez-Palencia *et al.* PRL 2007; Lugan *et al.*, PRA 2009), as confirmed by the group's experiments. The challenge was then to understand Anderson localization in correlated disorder in higher dimensions. We soon realized that it is almost impossible to create isotropic disordered speckle potentials in ultracold experiments. In 2010, we initiated a project to extend usual theoretical models and incorporate arbitrary correlation functions in the microscopic theory of Anderson localization. The project involves a combination of analytics and mid-scale numerical calculations. Using the computational cluster of LuMat (Univ Paris sud), we succeeded 2011, exactly at the time when the first experimental evidence of 3D Anderson localization appeared in the group. It placed us in an excellent position to analyze and interpret experiments, leading to an joint publication (Jendrzejewski *et al.*, Nat. Phys. 2012).

In addition, our analysis of the experiment suggested a significant improvement of the theory. Our approach provides the best present estimate of the mobility edge (Piraud *et al.*, EPL 2012) and of the effects of complex disorder correlations, for instance inversion of localization anisotropies and strength (Piraud *et al.*, PRA 2012). We have now started a collaboration with B. van Tiggelen (LPMMC, Grenoble) to further push the theory. By combining the knowledge of his group on Kubo formalism with ours on anisotropic disorder, we aim at designing a theoretical formalism that does not need a cut-off and may allow the treatment very strongly anisotropic cases. It will open new perspectives for ongoing experiments around the world (LCF, Urbana-Champain, LENS-Florence).

We have also studied Anderson localization in a disordered potential combined with an inhomogeneous trap, as relevant to ultracold-atom systems (Pezzé and Sanchez-Palencia, PRL 2011). We have shown that the energy spectrum displays both localized and extended states, which coexist at intermediate energies, an effect that is strictly forbidden in homogeneous disorder, according to Mott's argument. We have proposed a scheme to observe this effect and discussed its relevance for the damping of oscillations (Pezzé *et al.*, EPL 2009).

C.2 Disordered quantum gases: interactions, equilibrium, and dynamics

The most challenging issue in the field of disordered quantum systems is to understand the interplay of interactions and disorder. Many experimental projects, both in our group and elsewhere are developing along these lines (see 3.2). We have initiated a theory program in this direction, which has produced its first results and which is gradually becoming the center of our activities. On one hand, we have developed an analytical theory of many-body Anderson localization for weakly-interacting Bose fluids (Lugan and Sanchez-Palencia, PRA 2011). In 3D, our preliminary results show that the interplay of disorder and interactions is particularly rich. It can either protect the fluid from localization or lead to one or several mobility edges, depending on the model of disorder. This project will further develop towards Fermi gases, where the interplay of disorder and interaction should strongly differ.

In addition, we have started in 2012 a program towards strongly-correlated systems. We have developed large-scale Quantum Monte Carlo calculations, supported by the allocation of ~500000 computing hours per year on national clusters. Our code is among the most efficient ones worldwide and is able to simulate present-day experiments with no bias. We have computed the first quantum phase diagram of 2D interacting bosons in a continuous disorder. We have demonstrated that the superfluid transition is of the BKT universality class, and shown evidence of a bad metal behavior as a precursor of the Bose glass (Carleo *et al.*, PRL 2013). We are now extending this work to 1D and 3D systems where many questions remain open. We are also developing a real-time code able to capture dynamical properties, such as the postulated many-body finite-temperature dynamical insulator transition.

2. Reputation and academic attractivity

Awards between 2008 and 2013

In addition to Alain Aspect being recognized with prestigious awards such as the Wolf Prize in Physics, the EPS Quantum Electronics Prize and the OSA Yves Medal, several members of the group have received prizes: Chris Westbrook received the Prix Servant and Laurent Sanchez-Palencia the Prix Leconte, both from the Académie des Sciences, Philippe Bouyer received the Prix Jean Jerphagnon for innovation through research. Vincent Josse has been appointed a Junior Member of Institut Universitaire de France.

Major research Contracts

ERC Advanced Grant to Alain Aspect (QUANTATOP). This grant finances the quantum atom optics activities of the group (He* and BIARO), as well as the 3D Anderson localization project.

ERC Starting Grant to Laurent Sanchez-Palencia (ALoGlaDis). This grant finances the activities of the theory team especially the post-doc salaries

FP6 STREP to P. Bouyer (ISENSE) atom interferometry experiments

ANR grants: to Bouyer (MINIATOM), Westbrook (DESINA, CATS), Bouchoule (BOFL), Boiron (PROQUP), Bourdel (DisorderTrans)

Junior Chair of the Triangle de la Physique to D. Clément (CORSA)

DIM-SESAME (Ile de France) to C. Westbrook (DAISY)

Several grants via IFRAF, the Triangle de la Physique and the LABEX PALM

3. Interaction with the social, economic and cultural environment

Community outreach: Members of the Atom Optics group have actively participated in outreach programs, especially during the "Fête de la Science" held every year on the Orsay-Palaiseau Campus. Every year the group members have organized weekend lab visits for the general public as well as giving public demonstrations. D. Clément has also participated in two programs concerning public demonstrations of superconductivity (http://supraconductivite.fr) and quantum physics in general (http://www.toutestquantique.fr). We have also written several articles in various popular magazines (La Recherche) and commentaries on recent developments (Nature: News and Views, American Physical Society: Physics).

Interactions with industry: The work on atom interferometry has involved several partnerships with industrial labs. The MINIATOM project, in collaboration with THALES and ONERA developed laser systems and several other technologies for atom interferometers. Some of this work led to an important spinoff: the initiation by P. Bouyer of the startup company µQuans, an enterprise dedicated to developing a portable, commercial atom interferometer to make local measurements of the acceleration of gravity or its gradients. The company is also planning to use its technology to market a portable atomic clock based on cold atoms. The group is also presently collaboration with the group of S. Schwartz of THALES via the CATS program, a program discussed above.

Positions of responsibility within the French scientific community:

- Chris Westbrook:
  - Member of LABEX PALM steering committee, coordinator of the PALM topic "Quantum Correlated Systems" (2010-)
  - Member of the steering committee of the DIM NANO-K and co-coordinator of the "Quantum Gases" axis since 2011
  - Member of the steering committee of the Triangle de la Physique 2006-2011
  - Member of the evaluation committee for the ANR (SIMI-4 AMO and condensed matter physics) 2010-2012
- Philippe Bouyer: Member of the comité national du CNRS 2008-2012
- Isabelle Bouchoule: Member of the comité national du CNRS since 2012
- Laurent Sanchez-Palencia: Member of the steering committee of the Triangle de la Physique since 2011.

OPTIQUE QUANTIQUE

QUANTUM OPTICS

QUANTUM OPTICS GROUP MEMBERS

Head: **Philippe GRANGIER, Directeur de Recherche CNRS**

Faculty and Research Faculty holding permanent positions

« Atoms » Team	
BROWAEYS Antoine	Chargé de Recherche CNRS (directeur de recherche, 2013)
SORTAIS Yvan	Maître de Conférences IOGS/U. Paris-Sud, habilité
LAHAYE Thierry	Chargé de Recherche CNRS (arrived 2012)
« Photons » Team	
TUALLE-BROURI Rosa	Maître de Conférences U. Paris-Sud (IUT), habilitée
MESSIN Gaétan	Maître de Conférences IOGS/U.PSud, habilité
OURJOUMTSEV Alexei	Chargé de Recherche CNRS (arrived 2009)

Doctoral students

	Funding	**Start**	**PhD obtained**	**current position**
Simon Fossier	*CIFRE*	*Sept. 2006*	*Oct. 2009*	*research eng.THALES*
Alpha Gaëtan	*EDOM*	*Oct. 2006*	*Nov. 2009*	*on sabbatical*
Anthony Leverrier	*AMX*	*Sept. 2006*	*Nov. 2009*	*researcher INRIA*
Andreas Fuhrmanek	*EDOM*	*Oct 2008*	*Sept. 2011*	*consultant in Germany*
Franck Ferreyrol	*C'nano*	*Sept. 2007*	*March 2011*	*post doc Brisbane*
Charles Evellin	*AMX*	*Oct 2008*	*Nov. 2011*	*consultant Mazar group*
Rémi Blandino	*EDOM*	*Sept. 2009*	*March 2013*	*post doc Brisbane*
Ronan Bourgain	ENS Cachan	Sept. 2010		
Lucas Béguin	DGA/CNRS	Sept. 2010		
Erwan Bimbard	AMN	Sept. 2011		
Jean Etesse	AMX	Sept. 2011		
Joseph Pellegrino	EDOM	Sept 2011		
Sylvain Ravets	ENS Cachan	Sept. 2011		
Henning Labuhn	ITN Coherence	Jan. 2012		
Andrey Grankin	ERC Delphi	March 2013		

Visiting scientists and post-doctoral fellows

	Funding	**Start**	**End**
Aline Vernier	ERC Arena	Jan. 2011	April 2013
Radu Chicireanu	ERC Arena	Nov. 2010	Oct. 2011
Tatjana Wilk	SCALA + ERC	March 2008	May 2010
Yevhen Miroshnychenko	CNRS + SCALA	Sept. 2006	Aug. 2008
Andrew Lance	Marie Curie	Sept. 2006	March 2009
Valentina Parigi	ERC Delphi	Jan. 2010	Dec. 2012
Jovica Stanojevic	ERC Delphi	Nov. 2010	Nov. 2012
Andrew Hilliard	ERC Delphi	Oct. 2011	July 2012
Sanjukta Roy	ERC Delphi	Sept. 2010	Dec. 2010
Marco Barbieri	RTRA + EIF	Sept.2008	Aug. 2011
Imad Agha	C'nano + IOGS	Nov. 2008	Nov. 2010
Eleni Diamanti	IIF (CE)	Sept. 2006	Dec. 2008
Bhaskar Kanseri	CNRS	Nov.2012	Dec. 2013

Engineering support

The group benefitted considerably from the engineering support staff, and in particular Florence Nogrette, instrumentation engineer.

Master level trainees (for at least 3 months)

All doctoral students mentioned above started as master level students for a period of more than 3 months.
In addition, the group hosted about 10 master level students on shorter programmes.

1. SCIENTIFIC REPORT

The domain of expertise of the Quantum Optics group is the experimental study of specifically quantum properties of light. Since 2000, our work has been focusing on the **exploitation of the tools and methods of Quantum Optics, in the new domain of Quantum Information Processing and Communications (QIPC)**. The main idea here is to code and manipulate information written on quantum objects, so that a classical bit (0 or 1) becomes a quantum bit or « qubit », which can be in a linear superposition of the logical states 0 and 1. Two main applications of QIPC are now actively studied worldwide, and as we will see our group is active in both:

- **quantum communications,** and especially quantum key distribution (QKD): the general goal is to use quantum properties of the light to improve communications, e.g. to warrant secrecy from the laws of physics;
- **quantum computing:** by calculating with quantum registers made of qubits rather than classical bits, it is possible to design some algorithms which are exponentially faster than their classical equivalent.

Within the 4 last years, we have been pursuing two families of experiments along these lines:

(1) quantum optics, communications and cryptography with continuous variables. The idea here is to exploit the technique of pulsed quantum homodyne detection for application in QIPC. This work had several outcomes: a first one is a **new scheme for quantum cryptography with continuous variables**, which was initially published in « Nature »[2], and patented by us, and is now **developed in collaboration with the startup "SEQURENET"**. A second one is a family of methods to produce **quantum states for propagating light pulses, with a negative Wigner function**. An example of such a strongly quantum state is a « Schrödinger's cat », that we were able to observe and characterize using pulsed quantum tomography[3]. It should be noticed that our group had a ground-breaking role in this research field, with many papers quoted as « highly cited » by ISI, such as [2,3]. A third one, which started in 2010 within the ERC Advanced grant "DELPHI" ("Deterministic Logical Photon-Photon Interactions", PI Philippe Grangier) is to **implement "giant" optical non-linear effects, able to create photon-photon interactions**. This would open the way to photonic quantum logic, and to quantum information for "flying" qubits, especially suitable for quantum communications and quantum repeaters. The non-linear effect is provided by using so-called "Rydberg polaritons" in a cloud of trapped atoms inside an optical cavity.

(2) manipulation of individual atoms in microscopic optical dipole traps (optical tweezers). The leading trend of this experiment is to use **individual Rubidium atoms as qubits, in order to implement elementary quantum logic operations**. A lot of progress has been made since our first observation of single trapped atoms in 2001, and we have now very good atomic qubits, which can be moved using the tweezers, and entangled using "Rydberg blockade". Since 2010 this line of research is mostly supported by the ERC starting grant "ARENA" (Arrays of Entangled Atoms, PI Antoine Browaeys). Another line of research has also been started, using small ensemble of atoms inside the tweezers, rather than single atoms. The idea here is to study the physics of collisional interactions within a very small and very dense atomic sample.

In the following sections we shall briefly illustrate the main results obtained in these two domains.

A. Quantum Information Processing with Continous Variables

A.1 Quantum key distribution

Our team has been interested since 2000 in the possibility to encode information on amplitude and phase of a light pulse, or more precisely on its quadrature components, which correspond to the real and imaginary parts of the complex amplitude. Quadrature components are conjugate quantum observables, and according to Heisenberg uncertainty principle it is impossible to simultaneously measure them. We proved the possibility to exploit this fact for quantum cryptography and thus to encode a secret key on coherent pulses, *i.e.* on simple laser pulses.

After a first experimental proof of principle (ref. [2]) we worked, in close collaboration with the society Thales TRT, to the development and the implementation of such a system in a standard optical network. The really competitive performances of our prototype allowed us to be selected by the European network SECOQC for a real-size implementation on a secure optical network, organized in Vienna in October 2008 [NJP'09]. The system is stable and automatic, and has demonstrated continuous operation during 57 h, yielding an average secret key distribution rate of 8 kbits/s over a 9 km fibre with an attenuation of 2.8 dB.

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[2] *Quantum Key Distribution using Gaussian-Modulated Coherent States,* Grosshans F; VanAssche G; Wenger J; Brouri R; Cerf NJ; Grangier P, **Nature 421**: 238-241, Jan 16 2003 (ISI highly cited paper: top 1%, 299 citations in May 2013).

[3] *Generating Optical Schrödinger Kittens for Quantum Information Processing,* Ourjoumtsev A; Tualle-Brouri R; Laurat J; Grangier P, **Science 312** (5770): 83-86, Apr 7 2006 (ISI highly cited paper: top 1%, 235 citations in May 2013).

Then, in collaboration with Telecom ParisTech and with the start-up SeQureNet, the system was tested during six months over a distance of 17.7 km, within the frame of the ANR project SEQURE, showing the reliability of the prototype over a long period with a distribution rate of about 500 bits/s [Opt. Exp.'12]. More recently we have investigated, within the frame of the ERANET project HIPERCOM, new processing algorithms to enhance the extraction of secret keys, with a reconciliation protocol working efficiently at low signal to noise ratio: demonstrated rates were then of more than 2 kbits/s at a distance of 53 km, and 200 bits/s at a distance of 80 km [Nature Phot.'13].

***Figure 1**: Prototype for quantum key distribution with continuous variables. The system was then tested during six months over a distance of 17.7km, and an improved version reached a distance of 80 km.*

We have also explored different ways in order to further improve the range of QKD with continuous variables (CVQKD), such as efficient processing algorithms [PRL'09]. We have also studied the relevance of using an optical amplifier in the secure site just before detection, to compensate the finite efficiency of the detectors [J. Phys. B'09].

A.2 Non-Gaussian quantum states of the light

Quantum Key Distribution as described above cannot go beyond about 100 km, due to the attenuation in optical fibres. To reach longer distances, one must use the techniques of quantum information processing (QIP), such as quantum repeaters, remote entanglement, entanglement purification, which can improve the range of quantum communication protocols. In the field of continuous variables, non-Gaussian operations are mandatory to consider such processes, and heralded protocols are a simple and efficient way to implement such operations.

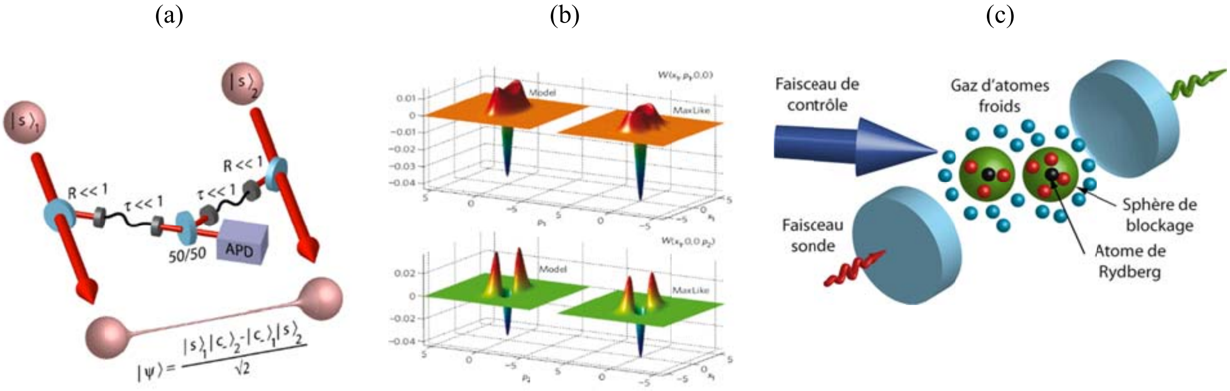

***Figure 2**: (a) Principle of remote entanglement: two distant states, initially non-entangled, are remotely entangled through a delocalized photon subtraction. (b) Some cuts of the four-dimensional Wigner function of the entangled pair, derived from a model and from experimental data (MaxLike), are presented. (c) Principle of photon-photon interactions using "Rydberg polaritons": photons are transferred to Rydberg states, and the excitation of a single atom creates a "blockade" effect on neighbouring atoms. This results in a "giant" optical non-linear effect.*

Heralded protocols, whose success is conditioned to a detection event, open a wide range of new perspectives in quantum optics. After the generation of free-space optical Schrödinger cats (ref. 3 on previous page), we demonstrated within the European project COMPAS, the possibility to perform heralded remote entanglement of such states [Nat. Phys'09], and investigated how this may improve the range of quantum repeater protocols [JOSA B'10]. Another possibility opened by heralded protocols is noiseless amplification, which can amplify a weak coherent state without added noise. If deterministic, such an operation would be forbidden, but its non-deterministic (heralded) nature makes it possible.

We performed the first experimental proof of principle of this quantum operation [PRL'11], which may allow a substantial improvement of the range of CVQKD protocols [PRA'12].

A major issue concerning heralded protocols is the experimental fidelity with the targeted operations, and the purity of the generated states. We therefore considered different means to quantify the quality of the experiment, and we developed various tools to represent heralded processes in terms of quantum maps for continuous variable states [PRA'12], to characterize a quantum gate for coherent-state qubits [NJP'12], to estimate the non-Gaussianity of the states generated by non-Gaussian operations [PRA'10], and to evaluate the Gaussian quantum discord for two-mode squeezed states [PRL'12]. We have also carried out, with colleagues from the Niels Bohr Institute of Copenhagen, a full theoretical modelling of phenomena that limit the performances of our experiments [PRA'09]. This work has highlighted the need for amplified pulses, and a pulse amplifier has been implemented in our setup: an increase of a factor four was demonstrated for the pump beam used in parametric amplification, with the subsequent increase of the parametric gain. This will allow reaching higher squeezing, but also higher state purity via the use of a larger pump beam. This work, supported by C'Nano - Ile de France, by the project MCQM of the RTRA "Triangle de la Physique", and by the ERANET project HIPERCOM, is still in progress.

A.3 Photon-photon Interactions using Rydberg blockade.

This project started in December 2009, in the Framework of the ERC Advanced Grant « DELPHI » (PI Philippe Grangier). The long-term objective is to create coherent and deterministic interaction between (individual) optical photons; obtaining such interactions is a major open problem in the domain of QIP, especially in view of applications in quantum communications. Our leading idea is to inject the "signal" light beam in a dense cloud of cold atoms, to excite these atoms to Rydberg states, and to use the very strong and long-distance Rydberg- Rydberg interactions to create dispersive optical non-linearities, acting at the level of a few photons only, see Fig. 2(c) above.

During the years 2010-11 a new experimental set-up was designed and built, with all the tools needed to trap the atoms inside an optical cavity, to prepare them in a well-defined ground state, and to excite them to Rydberg states with two lasers. Then we have observed a "giant" dispersive optical non-linearity as expected, though not yet at the single photon level [PRL'12]. In parallel, a series of theoretical works [PRA'11, PRA'12] allowed us to build up a detailed model for this experiment, and to predict how to extend it to the quantum level. In particular, we have demonstrated that the system can act as a "quantum scissors", and prepare a quantum state with a negative Wigner function, in a well-defined optical mode. Quantum tomography of such states is currently under way.

A.4 Squeezed vacuum using atomic vapours.

The experiments with non-Gaussian states described in section 2.2 are done using femtosecond pulses, and khi(2) non-linear crystals. We carried out another experiment in order to explore the possibility of transposing these techniques from the femtosecond to the nanosecond regime, using atomic khi(3) rather than khi(2) non-linearities. This would be more suited for applications using for instance (atomic) quantum memories. A first step towards this goal was to realize pulsed squeezing and pulsed entangled beams, from a (room temperature) cell of Rubidium atoms. The experiment was successful in demonstrating the generation of squeezed light using crossed-Kerr effect in a vapour of ^{87}Rb, both in the continuous and in the pulsed regime (with 200 ns pulses) [Opt. Exp.'12]. In addition, we demonstrated the generation of intensity-correlated pulses (the so called "twin beams"), using four-wave mixing in a double-lambda system, similar to the one used by Paul Lett at NIST in the CW regime. Excellent agreement was obtained with a model developed in collaboration with a team of University Paris Diderot [NJP'11].

B. Atoms in Optical Tweezers

B.1 Manipulation and entanglement of individual atomic qubits

Basic experimental set-up

The "atoms" team operates two experiments dedicated to the study of the interactions between a small number of ultra-cold rubidium atoms, with applications to quantum simulation and quantum information. The two experimental setups are based on a large numerical aperture lens (NA > 0.5) focusing a laser beam down to about 1 µm, thus producing a microscopic dipole trap (tweezers), as shown in figure 3. The tweezers is loaded from a magneto-optical trap (MOT). At low MOT density the number of atoms in the tweezers can be set to exactly one (single-atom regime), while for larger densities several hundred atoms can be trapped (multi-atom regime). During the period 2008 – 2013, the group has obtained major results using these two setups.

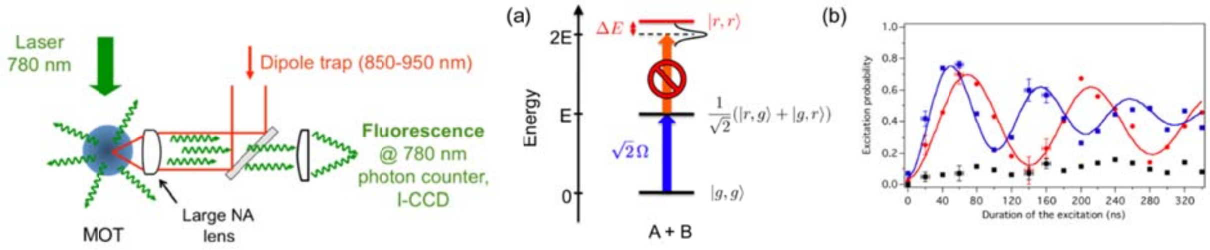

***Figure 3, left side**: Principle of the experiments for trapping rubidium atoms in a microscopic dipole trap (tweezer), loaded from a magneto-optical trap. The detection is ensured by collecting the fluorescence emitted by the atoms at 780 nm, which is sent onto a fibre-coupled photon counter or an intensified camera (I-CCD).*
***Center panel (a)** Principle of the Rydberg blockade between two atoms. **Right panel (b)** The blue curve represents the probability to excite only one of the two atoms in the Rydberg blockade regime as a function of the duration of the excitation. The red curve is the Rabi oscillation between the ground and Rydberg states when only one atom is present. The ratio of the two oscillation frequencies is √2.*

Demonstration of Rydberg blockade and entanglement of two atoms

Entanglement is an important resource in quantum information and simulation, but in 2008 a demonstration of the entanglement of two neutral atoms in their ground states was still missing. In 2009, we prepared a pair of entangled atoms using a method proposed in 2000 by the group of P. Zoller, which relies on the Rydberg blockade mechanism. The method makes use of the strong dipole-dipole interaction between two atoms excited to a Rydberg state that has a very large electric dipole moment. This strong interaction prevents their simultaneous excitation to a Rydberg state when the linewidth of the excitation is narrower than the interaction energy between the two atoms (see Fig. 3a). As any of the two atoms can be excited, but not both of them, the state of the two atoms after excitation is entangled, of the form (|r,g⟩ + |g,r⟩) / √2. Here |g⟩ and |r⟩ stand for the ground and Rydberg states respectively.

We have demonstrated the Rydberg blockade between two atoms trapped in two tweezers separated by 4 µm. The Rydberg excitation is ensured by a two-photon transition coupling the ground state $|g\rangle = |5S_{1/2}, F=2, M=2\rangle$ to the Rydberg state $|r\rangle = |58d_{3/2}, F'=3, M'=3\rangle$. Figure 3(b) shows the Rabi oscillation between the two states when only one atom is present. When the two atoms are present we observe a strong suppression of the probability to excite the two atoms, which is a demonstration of the Rydberg blockade. In order to demonstrate the production of a state of the form (|r,g⟩ +|g,r⟩) / √2, we measured the oscillation frequency of the probability to excite only one of the two atoms. This frequency should be √2 larger than the Rabi frequency associated with excitation of one atom when it is alone. We measured a ratio between the two frequencies of 1.38, very close to the predicted value (see figure 3b). This work was published in Nature Physics in 2009, and is an ISI Highly Cited Article (top 1%, 165 citations)[4]. Then by bringing back the Rydberg atom in a different ground state |g'⟩, we were able to entangle ground states atoms, with a fidelity of the entangled pair of 75%. This result has been published in Physical Review Letters in 2010, and is also an ISI Highly Cited Article (top 1%, 104 citations)[5]. Following this demonstration we have published several works on the detailed analysis of the Rydberg excitation of a single atom (PRA 2010) and the analysis of entanglement between two atoms, when the detection efficiency is not 1, as was the case in our experiment (NJP 2010).

We have then analyzed the limitations of our setup and, following the award of an ERC starting grant to the team, we have built a new setup dedicated to the physics of Rydberg atoms in an array of N~10 tweezers, with improved laser systems and full control over electric fields. The long-term goal is to create N-atom entangled states using the Rydberg blockade. Using this new setup we have already observed high-quality blockade between two atoms (less than 4% to excite the two atoms, to be compared to the result of fig. 3b).

Manipulation of individual atoms in optical tweezers

In the perspective of obtaining high-fidelity single atom manipulations, we have performed a series of experiments to characterize the external and internal degrees of freedom of a trapped atom. In particular, we have measured the energy distribution of individual atoms in the tweezers and showed that it is well described by a Boltzmann

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[4] *"Observation of collective excitation of two individual atoms in the Rydberg blockade regime"*, Gaetan A; Miroshnychenko Y; Wilk T; Chotia A; Viteau M; Comparat D; Pillet P; Browaeys A; Grangier P, **Nature Physics 5**: 115-118, Feb 2009.

[5] "*Entanglement of two individual neutral atoms using Rydberg blockade*", Wilk T; Gaetan A; Evellin C; Wolters J; Miroshnychenko Y; Grangier P; Browaeys A, **Phys. Rev. Lett. 104**: 010502, Jan 2010.

distribution, to which a temperature can be assigned (PRA'08). We have also developed an original time-of flight method for individual atoms (NJP'10). We have demonstrated a lossless detection of the internal state of a single atom based on fluorescence detection (see Fig. 4). This important result, published in Phys. Rev. Lett. (2011), will significantly improve the characterization of entanglement between several neutral atoms. We have measured the delay in the elastic scattering of near-resonant light by an individual atom, predicted by Wigner in 1954 and never measured in the ideal situation presented here (accepted for publication in Optics Letters, 2013).

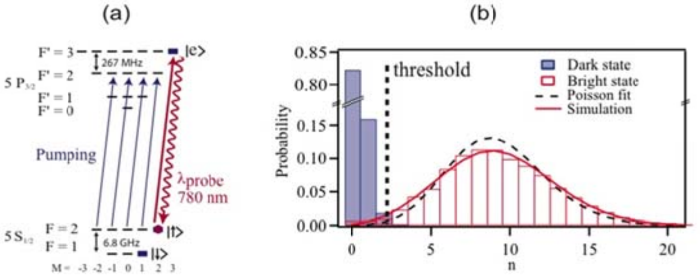


Figure 4. (a) Principle of the lossless, state-selective detection of a single atom, showing the states involved in the detection scheme. (b) Histogram of the number of photons detected at the end of the illumination period by a resonant probe when the atom is prepared in the dark (|↓⟩) or bright (|↑⟩) state. The vertical dashed line corresponds to the threshold for a fidelity of 98.6%.

B.2 Towards the study of small and dense atomic ensembles

During the reporting period, we have started the study of a dense ensemble containing a few hundred atoms trapped in the microscopic dipole trap. We have in mind to study quantum degeneracy in the few-atom regime, as well as the scattering of light by this atomic ensemble when the dipole-dipole interactions have to be taken into account. This system is ideal to study N-body physics in a rather pristine situation.

In this direction, we have studied the loading of microscopic dipole trap by up to a few tens of atoms. In particular, we have measured the (very high) light-assisted collision rate between at the fundamental level of 2-3 atoms (PRA'12). We have also implemented a method to count up to ~ 30 atoms in the dipole trap by the detection of single photons emitted by single atom. This method yields the average number of atoms, as well as its variance (PRA'11). Using this method, we have shown experimentally and theoretically that the variance of the atom number distribution in a dipole trap loaded from a magneto-optical trap is sub-Poissonian, and we measured a Fano factor (deviation with respect to the Poisson law) of 0.72±0.07, in very good agreement with the theoretical value 0.75 given by a stochastic model developed in the context of kinetics of chemical reactions (PRA'12).

2. Reputation and Academic Attractivity

Awards, Grants and Funding.

Alexei Ourjoumtsev received several awards for his thesis work (prix de thèse Paritech 2008, prix de thèse C'Nano 2009, prix de thèse de la Société Européenne de Physique 2009), and Philippe Grangier has been awarded the Grand Prix Jean Ricard (SFP, 2008), the Charles Hard Townes Award (OSA, 2012), and has been nominated a Fellow of the European Optical Society (2008) and of the Optical Society of America (2012). Rosa Tualle-Brouri was rewarded by a five year junior membership at the "Institut Universitaire de France". Antoine Browaeys was awarded an ERC Starting Grant "ARENA" (Arrays of Entangled Atoms, 2009-2014), and Philippe Grangier an ERC Advanced Grant "DELPHI" (Deterministic Photon-Photon Interactions, 2010-2015).

During the period, the team was involved in many European projects (SECOQC, COMPAS, AQUTE, HIPERCOM), in the Initial Training Network COHERENCE, and in the large scale IP SCALA coordinated by Philippe Grangier (2005-2009, 9.6 ME). Several postdocs were funded by individual Marie Curie European fellowship. The group was also involved in ANR projects (IRCOQ, SEQURE), and obtained financial support from C'Nano - Ile de France, IFRAF (Institut Francilien des Atomes Froids) and from the RTRA "Triangle de la Physique". It got also funding from the US agency IARPA through a collaboration with NIST Gaithersburg.

People, community activities, international programs and conferences

The team has a strong international dimension, with many foreign doctoral and postdoctoral students (from Germany, Italy, New Zealand, India, Serbia...), most often funded by European Grants. A new member, Dr Thierry Lahaye (CNRS-CR2) joined the team in january 2012. His main project is on the physics of interacting Rydberg atoms, under the supervision of Antoine Browaeys. The permanent staff members are regular reviewers for the ANR, ERC, and various national funding agencies, such as EPSRC (UK), New Zealand, Canada, Australia… They are also regular referees for scientific journals such as PRL, PRA, NJP, Science, Nature, Nature Physics, EPJ… The senior team members are also in many PhD thesis committees.

Gaetan Messin has many activities related to collaborations with China, and he is now coordinator of the GDR International Franco-Chinois « Quantum Manipulation of Atoms and Photons », which started in January 2001, for a 4 years period. He has been an Invited Professor at Beijing University, and he organized several French – Chinese workshops and conferences. He is also the representative of Institut d'Optique Graduate School in ECOP (European Centres for Outreach in Photonics) including ICFO, Imperial College, Vrije Univ. Brussel, NU Ireland Galway, Politecnico di Milano, Max Born Institute de Berlin and IOGS, with the general goal of promoting photonics.

Philippe Grangier has been co-chair (with Michèle Leduc, ENS Paris, and Hélène Perrin, U. Paris 13) of the 12th International Conference on Atomic Physics (ICAP 2012), that has been organized in july 2012 at Ecole Polytechnique. This large conference gathered about 1000 people, and was highly appraised by all attendants.

3. INTERACTION WITH THE SOCIAL, ECONOMIC AND CULTURAL ENVIRONMENT

All the CNRS team members are teaching in various places (Philippe Grangier and Antoine Browaeys at Ecole Polytechnique and in several Master 2 courses, Alexei Ourjoumtsev and Thierry Lahaye at ENS Cachan for Agregation, and in many students' projects). In addition, all team members participate in dissemination, though Open Days at the Institut or University ("Fête de la Science"), and broad audience conferences in various places, including Lycées (secondary schools) or "Nuits Blanches 2012" at Palais de Tokyo, Paris. We also write articles or comments in journals, including e.g. Science ("Perspectives") or Nature ("News & Views"), as well as popularization articles. Philippe Grangier has been President of the Physics Department of Ecole Polytechnique (09/2009 to 08/2012).

We worked, in close collaboration with the society Thales R&T and with Telecom ParisTech, to the development of a prototype for quantum key distribution with continuous variables, and to its implementation on a standard optical network. The start-up SeQureNet joined this collaboration, on the basis of patent applications filed during the previous period. By reaching a communication distance of 80km, this start-up can bring a really competitive product to the market, and it is now selling products. Philippe Grangier is in the Scientific Advisory Board of SeQureNet, and is closely collaborating with them, together with Eleni Diamanti ((LTCI, Telecom Paris).

NANOPHOTONICS AND ELECTROMAGNETISM

NANOPHOTONIQUE ET ELECTROMAGNETISME (NAPHEL)

NAPHEL GROUP MEMBERS

Heads:

BENISTY Henri	Professeur, IOGS/U. Paris-Sud
GREFFET Jean-Jacques	Professeur, IOGS/U. Paris-Sud
LALANNE[ℵ] Philippe	Directeur de Recherche CNRS (moved to LP2N in 2011)

Faculty and research faculty holding permanent positions:

BEN-ABDALLAH Philippe	Directeur de Recherche, CNRS (since Dec 2010)
CAMBOURNAC Cyril	Chargé de recherche, CNRS (left in 2010)
HUGONIN Jean-Paul	Maître de Conférence U. Paris 6 until 2009, "collaborateur bénévole" since 2009.
LAROCHE Marine	Chargé de recherche, CNRS (on leave since 2010)
MARQUIER François	Maître de Conférences IOGS/U. Paris-Sud
SAUVAN[ℵ] Christophe	Chargé de recherche, CNRS (LP2N in the period 2011-2013)

Doctoral students

VELHA Philippe	BDI CNRS, defended 2008	research scientist, Pisa
MILLET-RIBOT Céline	these CIFRE Thales, defended 2008	research engineer Safran
BOUGOT-ROBIN Kristelle	thèse CIFRE Thales, defended 2009	research fellow HKUST IAS
CHALOPIN Yann	allocataire ministère, defended 2009	chargé de recherrche CNRS
KHAYAM Omer	allocataire, defended 2009	engineer Infinera
MAZOYER Simon	Thèse DGA, defended 2010	research engineer St Gobain
ARCHAMBAULT Alexandre	allocataire DGA, defended 2011	research engineer
VASSANT Simon	allocataire Cnano, defended dec 2011	post doc Max Planck Erlangen
YANG Jianji	½ école doctorale EDOM and contract funding, defended 2012	
HABERT Benjamin	allocataire Cnano, 2010	
BIGOURDAN Florian	allocataire DGA, 2011	
LANGLAIS Mathieu	thèse CIFRE Total, 2011	
DHEUR Marie-Christine	allocataire DGA/CNRS, 2012	
LEFEBVRE Anthony	allocataire CEA, lab. CEA LETI, 2013	
JOUANIN Anthony	thèse CIFRE St Gobain, to be defended	
PISKUNOV Nikolay	allocataire co-tutelle Lomonosov, to be defended	césure

Visiting Scientists and Post Doctoral fellows:

BARON Alexandre	postdoc ANR CALLIN+ ATER IOGS (2010-2012, 24 months	postdoc CRPP
BIEHS Age	post doc Fondation Leopoldina (2009-2011)	Prof Univ Oldenburg
BRUCOLI Giovanni	post doc ONERA (2012-13) 12 mois	
COSTANTINI Daniele	post doc ANR IDEE (2013-) 24 mois	
KURT Hamza	post-doc IOGS (2007-2008, 12 mois)	TOBB Univ. (Ankara)
PANG ChengXin	post-doc ANR COHEDIO (2012-2013, 13.5 mois)	back to China mid 2013
DAHAN Nir	post doc ULTRACIS (24 mois, 2010-2009)	back to Israel
ESTEBAN Ruben	post doc ANR THRI-PV +LAPSUS (2009-2011)	research fellow San Sebastian
FRIEDLER Ingbal	post doc contrat Nano EPR, Nanoscience Europe (2007-08)	retour Israel
GAN Choon How	post doc ASTAR fellow ship (2009-2011) (24 mois)	post doc UK
MAKSYMOV Ivan	postdoc NanoEPR, Nanoscience Europe (2009-10)	res. fellow U. Western Australia
MESSINA Riccardo	post doc ANR (2012-2013)	CR2 CNRS Montpellier
da ROSA Felipe	post doc RTRA (2009-2011)	Prof Univ. Féd de Rio de Janeiro
ROUSSEAU Emmanuel	post doc ANR MONACO (2008-2010)	CR2 CNRS Montpellier
SMIGAJ Wojciech	postdoc triangle de la physique (2010-2011)	Ass. Prof. in Poznan Univ.
WANG Bing	post doc FET-SPLASH (2007-2009, 24 mois)	prof. Huazong University
LIU Haitao	guest professor 2006-2008 FFCRST + 2010 Poste Rouge CNRS	Prof. Nankai U.

Engineering support

The group benefitted considerably from the engineering support staff, and in particular Mondher Besbes, research engineer in scientific computing.

Master level trainee (co-author of publications)

YAN Chen	master M1, (mai-juillet 2011).	Doctoral student Univ Queensland

[ℵ] PL and CS joined LP2N, the Bordeaux laboratory of Institut d'Optique /CNRS, in January 2011, but their work has mostly been conducted at LCF or in association with LCF. It is partly presented in this report: "Metamaterials" and "Plasmonics of subwavelength surfaces" are reported here, "Slow light" and "Harnessing light in complex media" will be reported in the LP2N report next year. The scientific production is split chronologically (year < 2011: LCF, year ≥2011: LP2N).

1. SCIENTIFIC REPORT

The Nanophotonic group has undergone major evolutions during the period 2008-2012, with a large movement of key personnel. Philippe Lalanne left LCF for LP2N in January 2011. The arrival of J.-J. Greffet (Sep. 2008) and P. Ben-Abdallah (dec 2010) provided a bunch of new and exciting themes, with many students and post docs joining the group. Henri Benisty has participated to the dynamics of science and technology actively on many fields, including the (now aged) start'up Genewave.

The themes tackled by the group address the intersection of nanophotonics with important applications: radiative heat transfer, semiconductors and quantum photon sources, nanoantennae, plasmonics and quantum plasmonics, biophotonics, light-emitting diodes. It also proposes to revisit foundational concepts of (nano)photonics such as enhanced optical transmission, impedance for nanoantennae, many-body energy transfer, dark modes. We are listing the group activity along six entries that mix the individuals: the group feels that fluidity and thematic mobility are a premium in the area that should be fully encouraged.

The group relies much on high-level key technical LCF personal: Mondher Besbes for the *SimPhotonic* numerical tool and A.-L Coutrot and B.Ea-Kim for nanofabrication at the "PTC" (TRT-IOGS-X *Plateforme de Technologie Commune*). Yet, the development of the group experimental activities suffers from the lack of a full-time scientist working in experiment and nanofabrication. In spite of a relatively small size, (5 permanent positions on average over the last five years) the group has managed to publish 126 papers in peer-reviewed international journals, including 24 papers in journals with impact factor larger than 7 in the last five years. Among them, the theoretical paper on enhanced transmission was cited 230 times, the first experimental demonstration of heat transfer at the nanoscale was cited 111 times, the first demonstration of broadband and efficient single photon emission with semiconductor nanowires has been cited 130 times and five other papers were cited over 50 times. In what follows, we give a brief overview of key activities and results published after 2008.

A. Quantum Nanophotonics

i) Antennas for single photon sources.

Our strength relies on our dual expertise for both dielectric and metal nanostructures. We have been among the very first groups to propose new strategies to cope with classical critical issues of the domain, such as bandwidth, yield and efficiency in the first lens.

(a) plasmonic nanoantennae to control the Purcell factor and the emission direction [Science **308,** 1561 (2005)]. The designs of plasmonic patch nanoantennae or metal-coated semiconductor wires proposed in [PRL **104**, 026802 (2010)] and [PRL **105**, 180502 (2010)] have now been demonstrated experimentally [Nano Lett. **13**, 1516 (2013)], achieving Purcell factors up to $F_P = 80$ and focussing the light into a small solid angle.

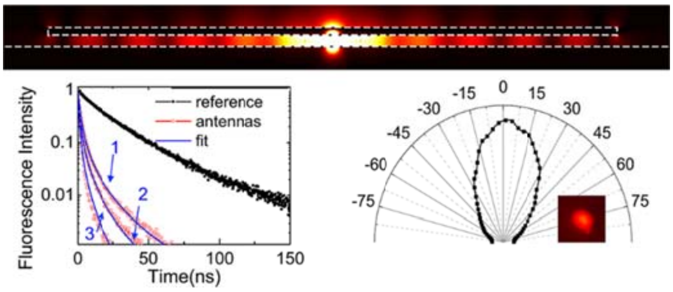


Figure 1. Top: schematics of the intensity distribution in a patch antenna, the source are a vertically oriented dipole located in the center. Bottom left: experimental measurement showing the acceleration of spontaneous emission; bottom right: far-field emission pattern. Collaboration: A Maître (INSP) and P. Senellart (LPN).

(b) Following our seminal proposal on achieving a *broadband* funnelling of the emitted photons into a single channel with dielectric structure [PRL **99**, 023902 (2007)], we have proposed new architectures with semiconductor nanowires. We solved the critical issue of designing efficient mirrors in tiny wires [Opt. Express **17**, 2095 (2009); coll. J.-M. Gérard, patent pending] and demonstrated a broadband single-mode emission with a state-of-the-art first-lens coupling efficiencies of 0.72 photon per excitation pulse [Nat. Photon. **4**, 174 (2010); coll. J.-M. Gérard]. Our ideas have inspired completely new all-solid-state-source constructs –see the works at Harvard, [Nat. Nanotech. **5**, 195 (2010)] and Deft Univ. of Technol. [Nat. Comm. **3**, 737 (2012)] for instance, and have received a wide appraisal as manifested by the 200 citations received by our works.

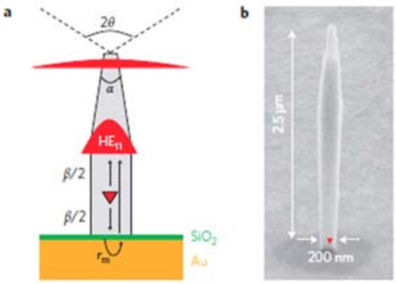


Figure 2: left: schematics of the nanowire antenna. Right: photograph of the nanowire antenna with a collection factor of 72%. Ref: Nat. Photon. **4**, 174 (2010)

ii) Hong-Hou-Mandel experiment with surface plasmons. This activity is on the verge of producing its fruits. We initiated a joint effort with QO's group to reproduce a key experiment of quantum optics with plasmons. While the quantization of surface plasmons was demonstrated by energy loss spectroscopy in the 50s', truly surface plasmon quantum optics experiments are still missing. We team with G. Messin (QO group), while P. Lalanne, J.-C. Rodier and J.-P. Hugonin have designed a plasmonic integrated circuit for testing various quantum phenomena and have validated the feasibility of the key components of the chip in collaboration with Ebbesen's group [*Nano Lett.*, **11**, 4207 (2011)]. G. Messin and F. Marquier have built an entangled photon source. M.-C. Dheur routinely observes the HOM dip in free space. The final step will be to couple the photons into the chip to observe the HOM dip for surface plasmons.

iii) Impedance of a nanoantenna. We have introduced a definition of the impedance of a nanoantenna and established the link with the local density of states [PRL **105**, 117701 (2010)]. This contribution unifies the quantum-optics and the electrical-engineer points of view.

B. GUIDED NANOPHOTONICs

The theme of guided nanophotonics has been renewed and explored in several respects:

- **Electrical modulation.** We have demonstrated electrical modulation of the reflectivity and emissivity in the THz at 34 µm. This *electrical* modulation is based on a novel concept for nanophotonics [PRL **109**, 237401 (2012)]. It is possible to shrink a 34 µm wave into a 20 nm thick GaAs layer taking advantage of what we have called the Epsilon-Near-Zero ENZ mode. There is a perfect overlap with electrons wavefunctions thereby enhancing the interaction and paving the way for ambient temperature THz optoelectronics.. An exquisite blend of fabrication talents at LPN, and team work at LCF allowed this success that has led to two patents for electrically tunable reflectivity and new detectors concepts.

- **Resonant cavities.** With Thales TRT (A. De Rossi & S. Combrié), we explored world-record high-Q PhC "Kuramochi-type" nanocavities on GaAs membranes with nanowatt-level nonlinearities, defined with the PCT's Nanobeam e-beam writer.

- **Photonic concepts:** Efforts have been attempted at blending concepts around known — or not-so-well-known — photonic structures, e.g. based on photonic crystals (with functional results, cf. a "CWDM demux" in Fig.3), broad waveguides, slow light, dark modes, nanocavities, plasmonic and dielectric waveguides, or, yet, for biochips, with the start'up Genewave and with Thales TRT.

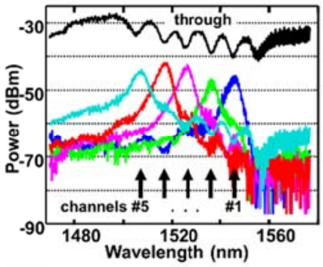


Figure 3: Spectra from improved coarse-WDM compact silicon-on-insulator 5-channels demultiplexer based on photonic crystal waveguide with lateral extraction. [J. Lightwave Technol. **28,** 1201 (2010)]

- **Parity-Time[PT]-symmetry.** We introduced a new theme, Parity-Time[PT]-symmetry, which in optics is realized by coupled loss+gain structures with real eigenvalues: we highlighted in collaboration with IEF mainly the fact that in well-designed coupled loss+gain systems, plasmonic losses *trigger* a singular effect. It can be for instance a large differential gain.

C. PLASMONICS

i) Fundamentals of subwavelength optical metal surfaces. The extraordinary optical transmission (EOT) phenomenon is a special case of Wood anomaly that results from the observation that light can be efficiently transmitted through periodic arrays of tiny holes drilled in metal film. To explain the abnormal transmission, the authors of the discovery built up on the Fano's model of grating anomalies and suggested that the incident light first scatters into surface plasmons (SPs) and that it is the SPs that subsequently tunnel the energy through the holes (Fig.4).

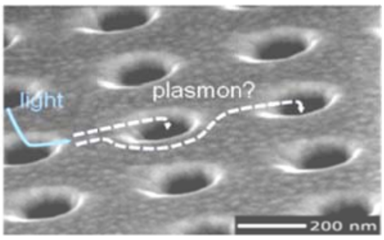


Figure 4 Initial surface-plasmon mechanism proposed to explain the EOT. The incident light first scatters into surface plasmons that subsequently propagate on the flat surface, couple to the hole and then tunnel the energy through the holes.

Following our initial rationale on the existence of two distinct waves (SPs and cylindrical waves) on subwavelength metal surfaces [PRL **98**, 153902 (2007), PRL **102**, 153903 (2009)], we first derived a "microscopic" model of the EOT and theoretically predicted that the SP are half responsible for the EOT and that they do not play a marked role [Nature **452**, 728 (2008)]. In collaboration with M. Van Exter in Leiden, we have just provided a firm experimental confirmation [Nature **492**, 411 (2012)] of the model, enabling a fit of the transmittance spectra of a series of hole arrays with different sparsities and many Wood anomalies with *only* five real coefficients. Note that the more advanced model of Wood anomalies (the so-called polology) requires five real parameters to fit a single resonance.

These works on the fundamentals of metal surfaces have been accompanied by several studies aimed at harnessing the generation of SPs with optimized subwavelength structures, either statistically [Surf. Sci. Rep. **64**, 453 (2009); APL **94**, 011114 (2009)] or dynamically [Opt.Express **20**, 15326 (2012)]. Some of our results, such as the compact SP antenna operating at normal incidence [Nano Lett. **11**, 4207 (2011)], provide state-of-the-art performances.

We have also generalized the microscopic model to derive analytical expressions for the real and imaginary parts of the refractive index of the emblematic *fishnet* metamaterials [PRL **107**, 043903 (2011)], allowing us to conceptualize how light flows into its different dielectric channels (in sharp contrast with homogenization approaches), and to provide an in-depth explanation for the appearance of a negative index.

ii) Fundamentals of surface plasmons. Surface_plasmons have two key properties: very large density of states and very large wavevectors resulting in strong confinement of the fields. The first property is responsible for large Purcell factor as discussed previously. It is also responsible for large energy density in local thermodynamic equilibrium and the basis for giant radiative heat transfer as discussed below. Regarding the resolution, while superlens promised unlimited resolution, actual demonstrations were limited by losses.

We have provided a firm theoretical basis for the discussion of these issues by clarifying the on-going debate on the dispersion relation of surface waves for lossy media [PRB **79**, 195414, (2009)]. This led us to predict that resolution is not fundamentally limited by losses. We have also clarified the fact that spatial resolution depends on the time structure of the incident light [PRL **109**, 097405, (2012)] showing that the resolution of Pendry's super lens could be significantly improved.

iii) **Super-resolution imaging**. We patented the merits of "fans of tips" with a small side in sub-λ "imaging", and a large side coupled vertically to a microscope. A paper was published in cross-team cooperation with F. Goudail.

D. Radiative Heat transfer at the nanoscale

i) Experimental study. Our group predicted in 2000 that surface waves can enhance the radiative heat transfer across a nanometric gap by several orders of magnitude. This is a consequence of the large local density of states close to interfaces due to the surface waves. We have published in 2009 a paper reporting experiments performed by E. Rousseau in collaboration with the group of J. Chevrier (Grenoble) reporting the first accurate comparison of experimental data with theory [Nature Photonics **3**, 514 (2009)] (see Fig. 5). This effect has been observed using a silica sphere brought in close proximity to a silica plane. The paper has been already quoted over 111 times and cited in two textbooks on nanophotonics and radiative heat transfer.

ii) Fundamentals of heat transfer at the nanoscale. The radiative heat transfer between two planes separated by a distance d diverges as $1/d^2$. This divergence has been considered to be unphysical by some authors. In order to analyse the physical meaning of this behaviour, we have developed a Büttiker-Landauer approach [PRL **105**, 234301 (2010)]. When linearizing the flux for small temperature difference, the flux is proportional to a quantum of thermal conductance per mode, a transmission factor and the number of modes which diverges as $1/d^2$. This approach has clarified the role of surface waves in the enhancement: they introduce a resonant transmission factor that compensates the exponential decay of the evanescent waves. Yet, they exist only for a very narrow spectral range so that this system is far from the maximum achievable heat transfer. We have set a new conceptual framework defining a blackbody analogue in near-field [PRB **82**, 121419(R), (2010)]. Subsequent work evidenced that anisotropic metastructures, and in particular the so-called "hyperbolic media", are good candidates to approach this "emissivity limit" [Opt. Express **19**, **A1088**, (2011); PRL **109**, 104301, (2012)] even without surface waves.

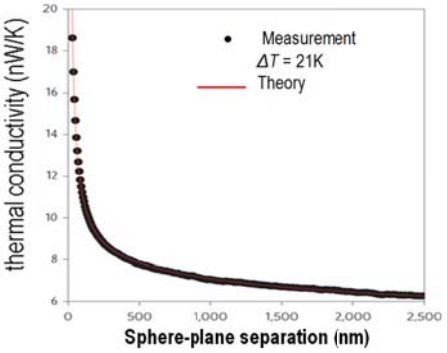


Figure 5: Thermal conductivity between a silica sphere and a silica plane and its enhancement in the nanogap regime (T ~ room-temperature)

We could, along a similar line, revisit the classical concepts of homogenization, generally used to describe the far-field radiated by a composite material, in the near-field region [APL **102**, 131106, (2013)]. This knowledge can now be usefully leveraged to explore a whole new level of complexity in material science, e.g. to design newly fabricated artificial materials possessing dedicated near-field properties.

iii) Heat flux modulators. Whereas electrical intensity can be easily modulated, controlling heat fluxes is much more difficult. Here, we have explored the possibility of taking advantage of the enhanced near-field radiative heat transfer to develop novel heat flux modulators. This idea was pursued along three avenues (i) we introduced a principle of mechanical modulation between twisted gratings [APL **98**, 243102, (2011)], which can be used up to a few kHz. (ii) Phase change materials with metal-insulator transition can attain the nanosecond range and were found more prone to reversible electrical modulation of heat fluxes [PRB(R) **84**, 161413 (2011); PRB(R) **83**, 201404 (2011)]. (iii) Graphene offers a germane opportunity to tune its plasmon and/or phonon-polariton emissive properties, through electrical Fermi level tuning of its local DOS [PRB **87**, 085421, (2013)].

iv) Thermoplasmonic in N-bodies systems. Until 2011 near-field heat fluxes between only two objects was explored. The often realistic case of a collection of mutually interacting objects, hitherto unaddressed, was described in a new dipolar approximation framework [PRL **107, 114301, (2011)**], resulting in a Meir-Wingreen-Landauer-type formula for the radiative heat flux through N-body interacting photon regions. Identification of enhancement mechanisms for three bodies highlights the promises of this approach. We thus proposed [PRL **109**, 244302, (2012)] to amplify the photon heat tunnelling using intercalated layers that over-compensate the intrinsic exponential damping of energy transmission. This leads also to heat exchanges at larger and more feasible separation distances, and could be crucial for thermal management at nanoscale, near-field energy conversion [Sci. Rep. **3**, 1383, DOI:10.1038 /srep01383, (2013)] and infrared spectroscopy.

v) Thermal relaxation at nanoscale by radiative cooling in near-field. We have performed the first investigation of radiative cooling of nano-object in the spirit of the environment-controlled changes of spontaneous emission (Drexhage 1974, Purcell 1946). The thermal Bose-Einstein distribution dictates here the emission rather than de-excitation processes. We investigated [Eur. Phys. J. B **85**, 233, (2012)] the dynamics of relaxation of nanoparticles at different distances from the surface of a bulk material and highlighted the existence of an oscillation for the thermal relaxation time as a function of the separation from the surface, an analogue of Friedel oscillations in Fermi liquids.

E. Controlling emission and absorption with nanophotonics

i) Controlling thermal emission. This line of research builds on one of the strength of the group who pioneered coherent thermal emission, demonstrating that a thermal source could be both quasi monochromatic and directional. We are now introducing the concept of actively controlled thermal emission [Nature **478**, 191 (2011)]. One demonstration of electrically controlled emissivity was reported recently [APL **102**, 081125 (2013)]. We could design coherent thermal sources, "thermal antenna", by proper surface texturing exploiting the coherence arising from surface modes [J. Appl. Phys. **109**, 034315, (2011)]. We then proposed a new concept of commutable thermal antenna from materials locally coated with metal-insulator phase change materials [PRB **84**, 161413, (2011)]. By controlling the material phase by optical, thermal or electrical means, the induced grating switches between a highly directional emissive state and a weakly emissive insulating state [Brevet FR68393, n° dépôt 12 61498], up to the MHz rate.

ii) Optimizing solar energy absorption. The group is involved in 3 programs devoted to optimizing absorption for solar cells. One of them addresses the grand challenge of designing a resonator operating for any incident angle and any solar frequency in order to absorb in an active layer as thin as 50 nm, as required for hot-carrier solar cells. We have designed a resonant structure that absorbs 66% of the incident photons [APL **97**, 221111 (2010)]. The second line of research revisits the validity of radiative transfer theory for ultrathin layers in order to model quantitatively the effect of scattering in solar cells in the context of CIGS [$Cu(In,Ga)Se_2$] solar cells. Finally, we also design selective absorbers that allow more than 85% of the incident flux for thermodynamics solar energy in collaboration with Total.

iii) Light extraction. Following the illuminating results on extraction from GaN-based LEDs brought until 2008 by the thesis of A. David (half at UCSB), a high-level review paper [Rep.Prog.Phys. **75,** 12651, (2012)] was published.

F. PERSPECTIVES

- **Quantum nanophotonics:** Besides the suite of the HOM activity detailed in §2, we will continue developing nanoantennae for single photon emission. Our goal is to increase the radiative efficiency of plasmonic patch antennas while keeping large Purcell factors using metallo-dielectric structures. Another direction will deal with many quantum dots interacting with plasmonic resonant nanostructures. This poses the issue of collective emission and absorption for solid-state emitters with a wealth of novel physics to be explored due to the presence of inhomogeneous broadening, dephasing and strong interactions.
- **Guided nanophotonics:** We will explore the potential of the PT-symmetry structures. We are also willing to explore the potential of the inverse-rib waveguides and developing new strategies to fabricate them.
- **IR incandescent sources:** A strong effort has just started on the development of novel IR incandescent sources. We envision developing sources that can be tailored to be directional, quasi-monochromatic, and highly efficient. We will also develop new sources with amplitudes modulated at frequencies above 1MHz using novel approaches including the ENZ effect and graphene based sources.
- **Solar energy:** Our efforts on solar energy will continue. Here, the key objective is to develop new absorbing structures which can efficiently absorb over a broad spectrum while reducing the active region thickness.
- **Radiative heat transfer at the nanoscale**: Our goals are: (i) to apply these concepts to near-field thermophoto-voltaics; (ii) to explore the potential of novel many-body structures including graphene structures; (iii) to conceive circuits for thermal light.
- **Electrical sources of surface plasmons:** While one of the key advantages of surface plasmons is the possibility of confining electromagnetic fields to sub-wavelengths volumes, their excitation usually involves diffraction limited beams. Hence, developing ultra-small electrical sources of surface plasmons is a critical issue. By taking advantage of the demonstrated source of lasing Tamm plasmon modes, we will design surface plasmons sources.

2. Reputation and Academic Attractivity

Invited lectures and review papers: The group members have given 67 invited lectures at international conferences and international schools since 2008. They have written 8 invited review papers or book chapters.

Impact: The papers written by the permanent researchers of the group have been cited over 8000 times in the last five years (ISI web of knowledge).

Project grants: The group has obtained 11 grants from ANR, 3 grants from CNano, 4 grants from RTRA and 2 grants from the european commission. It has also obtained two Procope (French-German) grants.

Collaborations: The group has collaborated with many partners: PMC(X), BIOC(X), Thales TRT, IEF (U-PSud), LPN, LPL (U-PSud), LNIO (UTT), UCSB (Mat Dept), HKUST (Institute of Adv. Studies & Physics Dept), Univ Ghent, Univ St Andrews, EPFL Lausanne, Dept of Physics (Univ Würzburg), Genewave, Soraa Inc.(USA), Dept of Physics (Lomonosov, Moscow), Institut Langevin, Univ Oldenburg, CEA, LPS Orsay, PPrime, Institut Néel, LPICM(X)

Scientific networks: The group members participate to the GDR “Ondes” and the international GDR "Nanoscale radiative Heat transfer". The group belongs to the Labex NanoSaclay (JJ Greffet is member of the board and head of the Nanophotonics flagship of the Labex). The group is also associated to the Equipex TEMPOS.

Scientific conferences: The members of the group are members of scientific committees of major conferences such as Near-Field Optics, SPIE, NanoMeta, Rad-13, EOS Annual Meeting. They have organized many national and international conferences: a session of META12 on diffractive optics, a session of META13 on parity-time-symmetry, a session of the JMC13 on Heat transfer and forces at the nanoscale, a school at Les Houches on "nanoscale radiative heat transfer", two sessions of IQEC/CLEO on Light-matter interaction at the nanoscale, an international workshop on Nanoantennae, the series of Nanophotonics Colloquiums of the Labex NanoSaclay.

Prizes: JJ Greffet received the Ixcore foundation Award and has been appointed senior member of the Institut

Universitaire de France. P. Lalanne became a fellow of the SPIE and was appointed Carl Zeiss visiting Professor at the Abbe School of Jena in 2010. H.T. Liu was the recipient of the 2008 Gilles Kahn Award of the FFCSA de l'Académie des Sciences for his work in our group on the extraordinary transmission. J. Yang received the Chinese Government Award for Outstanding Self-financed Students Abroad in 2013 for his PhD work on metamaterials. P. Ben-Abdallah received the Bronze medal of CNRS in 2009.

Post doc and invited professors: the group has hosted one invited professor (HT Liu, 18 month) and 16 postdocs.

Editorial committees: H. Benisty is the Editor of "Photonic and Nanostructures, Fundamentals and Applications" (Elsevier, IF:2). P. Lalanne is in the editorial board of Laser & Photonics Reviews (Wiley, IF:9).

3. INTERACTIONS WITH SOCIAL, ECONOMIC AND CULTURAL ENVIRONMENT

Patents: 5 patents have been filed.

Industrial collaboration:

- Research contract "Optiss" with Total.
- One ANR project in collaboration with the company DeltaDore towards the design of IR emitters for gas detection.
- One ANR project in collaboration with Horiba. One ANR started in 2013 with Morpho and Nikkoia.
- H. Benisty is a founding member of the company Genewave, now merged with Mobidiag (april 2013). He is also a consultant for Genewave, L'Oréal and a coach for Archimej incubation.

Outreach activities:

H Benisty and PhD students were actively involved in the exhibition at Palais de la Découverte *"Un chercheur, une manip"*. A 1-meter-size, dynamic, LED-lit, “Photonic Crystal Cavity” mock-up has been realized by the Palais'workshop. It has been further duplicated for use in the “Nano-Ecole” housed at IEF.

- Members of the group participate to the "Fête de la Science" every year.
- 9 conferences for highschool students and/or highschool professors have been given.
- JJ Greffet was member of the organizing committee for the celebration of Lippman's Nobel Prize centenary.
- The group organized a one day event on nanophotonics for "classe préparatoires" professors.
- 5 papers have been published in Photoniques, Bulletin de l'Union des Physiciens or Images de la Physique.

NONLINEAR MATERIALS AND APPLICATIONS

MATERIAUX NON LINEAIRES ET APPLICATIONS (MANOLIA)

MANOLIA GROUP MEMBERS

Head: PAULIAT Gilles   Directeur de Recherche, CNRS

Faculty and research faculty holding permanent positions

ROOSEN Gérald	Directeur de Recherche CNRS (départ retraite, janvier 2009)
FREY Robert	Directeur de Recherche CNRS (départ retraite, 2010)
DELAYE Philippe	Directeur de Recherche CNRS
CUNIOT-PONSARD Mireille	Chargée de recherche CNRS
JONATHAN Jean-Michel	Professeur IOGS/U. Paris-Sud
LEBRUN Sylvie	Maître de Conférences IOGS/U. Paris-Sud
DUBREUIL Nicolas	Maître de Conférences IOGS/U. Paris-Sud, habilité

Research engineer

DESVIGNES Jean-Michel	Ingénieur CNRS, (départ retraite, septembre 2008)

Doctoral students

ASTIC Magali	allocataire, defended December 2008, ingénieur recherche IMEP-LAHC
BARON Alexandre	allocataire, defended December 2010, post-doc CRPP Bordeaux
KROEGER Felix	allocataire, defended December 2010, Ingénieur à Deutche Telekom
CHARLET Gabriel	full time engineer, defended February 2011, research engineer at Alcatel
CONTRERAS Kevin	allocataire, defended February 2011, post-doc UCL, Louvain La Neuve
SHAN Liye	allocataire, defended December 2012, back to her home country
ODEN Jérémy	allocataire, 2010-
BARBIER Margaux	allocataire DGA, 2011-

Visiting scientists and post-doctoral fellows

TREBAOL Stéphane	ATER 2010-2011,
RYASNYANSKIY Aleksandr	Post Doc, octobre 2007- septembre 2009
JOHN Beena-Mary	Post Doc, Sept 2007 août 2008
TONG Limin	Prof. Invité Erasmus Mundus avril-juillet 2008
VIENNE Guillaume	Prof. Invité Univ Paris Sud janv. -2008
BUY Christelle	ATER 2009-2010,
PHAN-HUY Minh Châu	Post Doc 2009-2010 et 2010-2012
AGRAWAL Govind P.	Prof. Invité, 18 mai- 19 juin 2009.

Master level trainees (for at least 3 months)

ABUALROB Hadil	Stagiaires Erasmus, 3 mois en 2010
ARCHER Justice	Stagiaire M1, 3 mois en 2010
ILIESCO Eddy	Stagiaire L3, 3 mois en 2011
DONG Renxing	Stagiaire M1, 3 mois en 2011
FAN Bo	Stagiaire 1A IOGS, 3 mois en 2011
LEBLANC Nicolas	Stagiaire Erasmus Mundus, 3 mois en 2011
OYOUMBA Wilfried	Stagiaire M2, 3 mois en 2010
DE Syamsundar	Stagiaire M2, 3 mois en 2011
DEROY Julien	Stagiaire M1 IOGS, 3 mois en 2009
KOPTYUG Irina	Stagiares, Erasmus Mundus M1, 3 mois en 2009

1. SCIENTIFIC REPORT

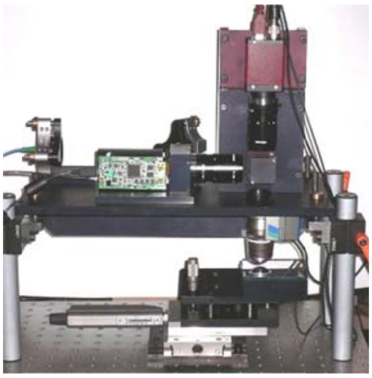
As so many other research groups worldwide, we investigate nonlinear optics. We nevertheless make our difference by mastering the complete chain going from the physics of the nonlinear optical interactions to the implementation of optical functions until the development of the applications and their relative know-how transfer toward the industry. We want to maintain this specificity by systematically examining the applicability of our research outputs trying to transfer them whenever possible. As an example, the research conducted on Stimulated Raman Scattering during the period 2003-2008, now becomes our strongest valorisation project.

Our major research results are reported below. In the coming years, we intend to pursue each of these research topics along the lines depicted in each paragraph. We have launched a new topic named "evanescent nonlinearities with nanofibres". This topic seems to be rich in terms of physics and applications. We will probably give this topic a stronger importance in the near future.

We are also very concerned about the possible answers that nonlinear optics could bring to major societal challenges. Some of our current researches are already motivated by these issues (long term data archiving). We permanently explore new potential research topics conforming to these requirements. We have identified such a new hot topic in the area of optical communications in which we could apply our vision of nonlinear processing. Although we have just conducted our first modelling on this topic, "Optical data mining for telecommunication", we think we may contribute to break the deadlock of optical network capacity. We therefore shortly describe it in a dedicated paragraph "Optical data mining for telecommunication".

A. Very long term data archiving

Until recently, the biggest challenge in data storage was producing devices with ultrahigh capacities. We have been working along this line and developed during the last period the so-called "Lippmann data storage technique". We demonstrated that this robust optical data storage technique should lead to capacities larger than 1 TByte for a 1 mm thick disk of 12 cm in diameter. However, the archiving life of this storage system is limited to a few tens of years by the degradation of the photopolymer used for data recording. This limitation is severe. Indeed, data storage is facing a new unexpected challenge. While our modern society produces more data every day, the lifetime of our mass storage devices is shorter than the period over which the data need to be stored. Medical data should be stored for periods longer than the patient life, public administrations, banks, libraries, mining, movie industries should even store data over more than 100 years. We thus reconsider this data storage problem on how to store data under a high density for archiving over centuries. These thoughts are conducted through our participation to the GIS SPADON (Groupement d'Intérêt Scientifique sur les Supports Pérennes d'Archivage des DOnnées Numériques), and to the "Archive & Forget" project. This project, led by the company GLAZT, http://glazt.com/, aims at realizing CD like disks made of glass for archiving. Although the first goal of Archive & Forget is to reach archiving lives larger than one century, with our partners in this consortium we also propose storage solutions regrouping the issues of both archiving life and ultra highcapacity.



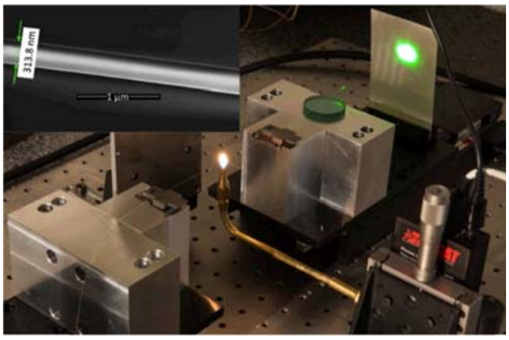
Read/write data storage system. A spatial light modulator is used to encode pages of data on a wavelength tuneable wavefront. Data are wavelength multiplexed in the same location of the recording material. Various locations are addressed with the XY moving platform.

In parallel, with B. Poumellec and M. Lancry from the ICMMO (Orsay), we have started our modeling on volumetric data storage by small refractive index perturbations written in the volume of silica by picosecond pulses. The first estimations anticipate TByte capacities and archiving life times over centuries. We now intend to validate these modellings by a first experiment. If, they are validated, and if this architecture confirms its compatibility with the technological issues of a compact and robust read-write device, then we will increase our effort on this topic in the coming period.

Collaborations: Glazt; LOMA Bordeaux; ENSAM-IS2M Mulhouse; ICMMO, Orsay.

B. Stimulated Raman Scattering in nanofibres

In 2008 we launched a new research project on nanofibres. These tapered nanofibres are optical fibres stretched until their diameter becomes comparable to the optical wavelength. At these small diameters, the guided light exhibits a pronounced evanescent field that extends outside the fibre and senses the surrounding medium. We anticipated that significant optical nonlinearities, also called "evanescent nonlinearities" could be excited in this surrounding medium. In collaboration with prof. L. Tong (Zhejiang University, China), we developed a pulling platform, see figure, specially designed to draw nanofibres optimized for this demonstration of evanescent nonlinearities. We now perfectly control their profiles: their diameters can be as small as a few hundreds nanometres over lengths up to 10 cm. In spite of these small diameters, their transmission remains larger than 90%. Our first demonstration concerned stimulated Raman Scattering in a liquid probed by the evanescent field of a tapered silica nanofibre. We either used a pure liquid, ethanol, or a mixture of liquids, toluene diluted in ethanol to control the refractive index and evanescent field. Very efficient Raman conversion up to the second Stokes was evidenced with a low power sub-nanosecond microlaser.



Platform for pulling nanofibres. The two computer controlled translation stages pull the fibre that is heated by the flame. Inset: scanning electron beam microscope image of a nanofibre.

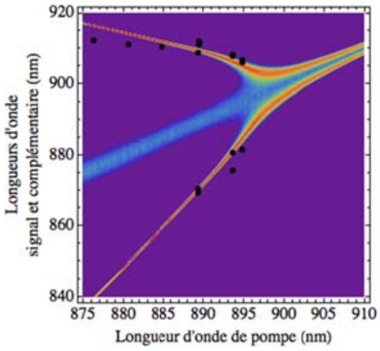
Given the large choice of available materials for the medium surrounding the nanofibre, the optical dispersion can be engineered and the nonlinearity can be optimized. These demonstrations pave the way to the exploration of a new class of experiments and devices. We pursue this work with Prof. L. Tong. Next, we thus want to investigate parametric four wave-mixing in these systems. We also expect a strong surface second order nonlinearity. This would allow the creation of compact quantum sources based on parametric fluorescence, sources whose main advantage being to deliver photons optimally matched to a telecom fibre mode, making them ideal for lossless connections to fibre optic networks.

In parallel, this year, we started to collaborate with J.C. Beugnot, from Femto-ST in Besançon, to investigate Brillouin scattering in nanofibres. We pulled nanofibres whose diameters and lengths were optimized to enhance the Brillouin effect. The first published results show that the acoustic confinement in the nanofibre allows the propagation of new and strong acoustic modes, such as surface acoustic waves. The strong acoustic coupling with the environment should favour the operation of sensors. We work in this direction.

Collaborations: Prof. L.M. Tong, Zhejiang University, China; J.C. Beugnot, Femto-ST, Besançon.

C. Parametric four wave mixing in hollow core microstructured fibres

The search for efficient and high quantum quality source of pairs of entangled photons has been the object of numerous researches in the last twenty years. Recently, third order nonlinearities in fibres were proposed as a solution with multiple advantages among which the high brightness and the possibility to easily connect, with low losses, these sources to the optical communication networks. Nevertheless these sources suffer of the low quantum quality of the emitted pairs corrupted by uncorrelated Raman photons generated by the glass core. The Raman spectral bands are indeed very large and close to the signal bands. We propose to improve the quality of the photon pairs by using liquid filled hollow core photonic crystal fibres. Raman photons are still unavoidably generated, but they originate from the liquid core. The Raman spectral lines are then much narrower and widely spaced than in glass. They can now be easily filtered out.



Experimental phase matching curve deduced from the dispersion measurement of the acetone-d6 filled hollow core fibres. The points correspond to the measured position of the parametric amplification maximum.

We have implemented a set-up to observe and characterize correlated pairs of photons in such liquid filled hollow core photonic crystal fibres. We have currently observed optical stimulated amplification in a pump probe regime with position of gain maximum coherent with the phase matching curve.

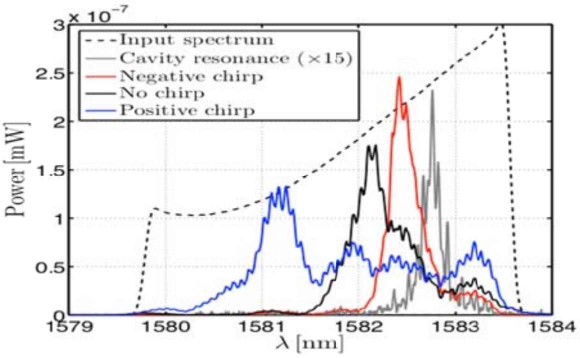
In the very near future, we will observe the photon pairs generated in the spontaneous regime. The characterization of these pairs will allow comparing the brightness and quantum visibility of our source with existing sources and with theoretical models. This will open the way to observe the generation of entangled pairs in collaboration with LTCI, and the design of new optimized fibres with our partners of XLIM, but also the design of new multi-pump four wave mixing set-ups such as "Bragg scattering" experiments for frequency conversion of single photons.

Collaborations: Isabelle Zaquine, LTCI Telecom ParisTech; Fetah Benabid, XLIM (Limoges).

D. Non linearity enhancement in slow ligh waveguides and microcavities

Since their apparition twenty years ago, photonic crystal structures have attracted a large amount of research and application proposals. Among their various properties, light localization in slow mode waveguides and microcavities gives strong promises for the increase of nonlinear performances of photonic devices. Our researches have thus focused on the theoretical and experimental demonstration of the enhancement of nonlinearities in these structures. We have thus realized the first experimental quantitative evaluation of the influence of light confinement on nonlinearities in a slow mode waveguide. We demonstrated that a new hierarchy between nonlinear mechanisms has to be considered in the conception of devices such as Raman amplifiers or Kerr switches.

This comprehension of the interaction between nonlinearity and microstructuration, allied to a constant development of our experimental tools for the characterization of these structures, has led us to propose a new technique for controlling that interaction between nonlinearities in photonic crystal devices. We have thus realized the first demonstration of the application of the coherent control technique to compensate for the resonance shift due to carrier effect and thus to maximize the injection of short pulse energy in a nonlinear microcavity (see figure).



Measured spectra transmitted under various tailored chirped pulse excitations. With the correct positive chirp (blue curve), a larger energy is injected in the cavity.

In collaboration with IEF, Orsay, we are now starting to study slow-mode SOI photonic crystal slot waveguides. Slot waveguides are empty-core planar waveguide that can be filled by strongly nonlinear optical materials. Such materials could be polymer embedded carbon nanotubes such as the ones we are going to study in collaboration with the Nanyang Technological University of Singapore. In the longer term, using these new high efficiency materials and our coherent control tools, we intend to study and manipulate the dynamics of coupled nonlinear microcavities.

Collaborations: Antoine Godard, ONERA-DMPH, Palaiseau; Éric Cassan, IEF, Orsay; Thales Research and Technology; G.P. Agrawal, Institute of Optics, Rochester ; Kin Kee Chow, Nanyang Technological University, Singapore.

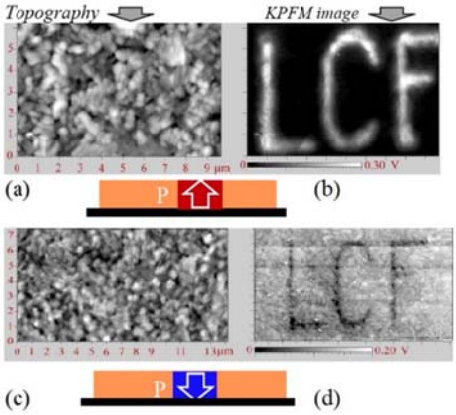
E. Strontium Barium Niobate (SBN) thin films for electro-optic and non linear photonic applications

The drive towards miniaturization and the development of photonic crystals have oriented researchers towards the preparation of nonlinear materials in the form of thin films. These open the path to the realization of future photonic devices like waveguide modulators with a voltage-length product lowered by orders of magnitude, or electrically-tunable photonic crystals. Electro-optic thin films may be obtained either by crystal slicing and wafer bonding or by epitaxial deposition. Efforts reported in the literature have focused on the primary electro-optic material $LiNbO_3$ and some titanates (BST and PLZT). We chose to develop strontium barium niobate epitaxial thin films ($Sr_xBa_{1-x}Nb_2O_6$, noted SBN : 100x) because this ferroelectric material exhibits an exceptionally high electro-optic coefficient, greatly exceeding that of $LiNbO_3$. A second motivation to prepare SBN in the form of a thin film is it makes it easier to engineer ferroelectric domains using an atomic force microscope. Domain patterns may be designed and “engraved” in view of optimizing a quasi-phase-matching regime used for wavelength conversion.

The implementation of SBN electro-optic properties requires a successful hetero-epitaxial growth of the film with (001) SBN direction perpendicular to a lattice-matched conductive substrate plane. A (001) SBN // (001) Pt // (001) MgO double epitaxial growth has been achieved by using the RF magnetron sputtering of Pt and ceramic SBN targets. Our films exhibit ferroelectric properties close to those of SBN crystals and a strong dielectric non linearity at room temperature.

Standard methods of measuring electrooptic coefficients in a thin film use approximations that strongly affect their reliability. For this reason we have developped an original method that does not use any of these approximations. The electric field induced variation in the reflectivity of a [electrode/film/electrode/substrate] stack is measured versus incident angle and optical polarization. The magnitudes and signs of the electro-optic, converse piezoelectric, and electro-absorptive coefficients of the film can be simultaneously and unambiguously determined from these measurements. Converse-piezoelectric and electro-absorptive effects have been found significant in the film response at a frequency below piezoelectric resonance. Diagonal and effective EO coefficients of a SBN film are measured larger than those of a crystal of lithium niobate (LN) at the same wavelength λ=633 nm. Further improvements are under investigation.

Atomic Force Microscopy provides the means to write, read, and investigate local polarization in a thin film. The SBN response to a poling process has been investigated using the Kelvin Probe Force Microscopy (KPFM). We have established the relationship between the KPFM signal and the polarization in a poled film area below the tip. It is exploited to quantitatively investigate the role of poling parameters or deposition conditions as well as the stability of the written polarization. We aim at the realization of test devices.



KPFM images (b, d) of two areas in a SBN film where the three capital letters LCF have been previously "written" by moving the biased tip in contact with the surface. The topography is shown on the left of each KPFM image (height scale is a few tens of nanometers). The poling voltages applied to the tip were -10 V (top image) and +10 V (bottom image) so that the written polarization had the direction indicated below each image.

Collaborations: FEMTO ST, Besançon; LMOPS, Metz; IEMN, Lille.

F. Optical data mining for telecommunications

Space division multiplexing is seriously considered as one of the very few possibilities to increase the capacity of telecommunication networks. Each spatial mode of a multimode fibre is treated as a single mode fibre that already contains a given number of data channels. Using multimode, instead of singlemode, fibres should thus increase the capacity by a factor equal to the number of spatial modes. Nevertheless, the current implementations are strongly limited to a few spatial modes by the unavoidable cross-talk between them.

We propose to by-pass this cross-talk problem. We still want to work on spatial multiplexing, i.e. to increase the capacity by using a multimode fibre, but we do not consider that a data channel should necessarily be conducted by a single spatial mode. We propose to work directly on the data channel, no matter this data channel is carried by a single spatial mode or spread over several modes. A data channel spread over several spatial modes can indeed be optically identified: it is fully spatially coherent. Demultiplexing N data channels is thus equivalent to separate the multimode fibre output into N spatially fully coherent beams. We master the tools to measure the spatial coherence (ex. interferometry) and to manipulate it (filters with nonlinear optics or spatial light modulators). We thus propose new schemes to enhance the spatial coherence of an optical beam, i.e. to extract a data channel from this beam. Based on these tools, we also plan to realize full self-organizing systems able to automatically separate the data channels. These self-organizing systems share many features in common with the self-organizing laser cavities we previously developed in which the cavity automatically selects one coherent mode from a series of spatial and spectral modes.

We have started the first analyses this year. We now intend to perform the first experiment to validate our proposal. Using two data channels spread over the modes of a multimode fibre, we plan to demonstrate that a non-linear optical processor can efficiently separate the output in two beams, each of them being spatially coherent, thus corresponding to one of the two data channels.

2. Reputation and academic attractivity

Group members serve as chairmen of scientific meetings (Topical meeting of the EOS, Horizons de l'Optique) and participate to scientific committees or organizing committees of numerous scientific conferences. They also serve in editorial committees (JEOS:RP) and as referees for various scientific journals. They act as experts for research projects (ANR, ANRT,…) and recruitment selection committees ("commissions de spécialistes").

Gilles Pauliat is a member of the board of the French Optical Society. He has just finished his last term as a board member of the European Optical Society at the end of 2012. He was also a member of the EOS fellow committee.

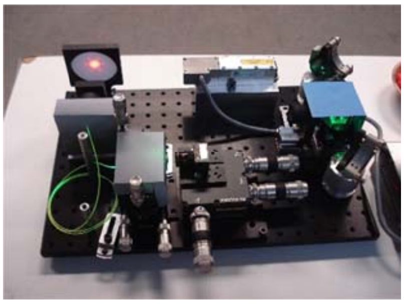
Gilles Pauliat is also member of the Scientific Council of Holo3, Saint Louis France, a centre of technology transfer specialized in optics.

3. INTERACTION WITH THE SOCIAL, ECONOMIC AND CULTURAL ENVIRONMENT

Scientific assistance and know-how transfers

Whenever possible we try to make our expertise and know-how useful for the industry. Except for the first contacts, our discussions are always conducted under the cover of a Non Disclosure Agreement. During the last period, we have signed 6 such NDA agreements (Essilor, Bayer, Horiba Jobin-Yvon, Opton, LMDC, Doremi). We also finalized the transfer of our know-how on the photorefractive sensor to ESPCI, that now completely takes care of these set-ups for ultrasonic imaging in scattering media.

We now put our strongest efforts toward the industrial exploitation of our previously developed research results on "wavelength conversion by Stimulated Raman scattering in liquid filled hollow core photonic fibres": our Rambio project. These Rambio converters allow obtaining any wavelength among a full series of wavelengths by just connecting a Rambio fibre to the output of a fixed wavelength laser. This project won the award "Fibre de l'innovation" in 2011. We protected its realization by a patent in 2012. First tools have been elaborated to repetitively fabricate these converters. In 2012, we showed one Rambio demonstrator (see figure) at the OptDiag conference in Paris.



Rambio wavelength converter presented in operation during the OptDiag conference. The commercial green microlaser beam is converted in a red diffraction limited beam by the wavelength converter (fibre in the bottom left hand corner).

In collaboration with industrial and academic partners (IMMC (Orsay), LMDC, Horiba,…), we now investigate the applicability of this technology to different potential markets: oncology, dermatology and fluorescence microscopy.

Education Management

Group members are strongly involved in teaching management: Jean-Michel Jonathan manages the "École Supérieure d'Optique"; Sylvie Lebrun is the education manager of the second year of ESO; Nicolas Dubreuil coordinates the two year Master programme "Optique Matière Plasma".

Science popularization

We regularly contribute to the popularization of science. Our background activity is represented by our routine implication in the "Fête de la Science", and by articles in large audience publications, Photoniques, Optics and Photonics News. We are also involved in much more absorbing actions. For instance, we were very strongly involved in the organisation, research of sponsors, design and set-up of the exhibit "Un monde en couleurs: de Gabriel Lippmann à la nanophotonique" that was presented during one year (June 2009-May 2010) in the Palais de la Découverte in Paris. This exhibit has then been moved as a travelling exhibit in the cities of Cachan and Luxembourg. It has been seen by tens of thousands of visitors.

Partial view of the exhibit presented in Palais de la Découverte in Paris with our reproduction of an « iconoscope » (historical viewer for Lippmann's picture)

BIOPHOTONICS

BIOPHOTONIQUE

BIOPHOTONICS GROUP MEMBERS

The Biophotonics group was established in July 2011.

Head: CANVA Michael Directeur de Recherche, CNRS *(Visiting Scientist, Duke University, Sept. 2009 - August 2010).*

Faculty and research faculty holding permanent positions:

DUBOIS Arnaud	Professeur IOGS/U. Paris-Sud
MOREAU Julien	Maître de Conférences, IOGS/U. Paris-Sud
PERRONET Karen	Chargée de Recherche, CNRS
WESTBROOK Nathalie	Professeure IOGS/U. Paris-Sud

Doctoral students

BLAVIER Marie	CIFRE CTP, defended Jan..2008, ingénieur CDD Observatoire Meudon
DUVAL Aurélien	Allocataire UPSud, defended July 2009, chercheur vacataire Canada
HOTTIN Jérôme	CIFRE Genoptics, defended July 2009, post-doctorant U. Lille
DULIN David	All. UPSud, thèse sout. Oct. 09, post-doc à Bionanosciences Dpt TU Delft
SACCHET Delphine	Allocataire UPSud, defended July 2010, prof. classes préparatoires
DEVAUGES Viviane	Allocataire UPSud, defended en Dec. 2011, post-doc King's college UK
LE GALL Antoine	All. UPSud, defended Nov. 2011, post-doc au CBS, Montpellier
NAKKACH Mohamed	Divers dont groupe, defended July 2012, enseignant-chercheur Tunisie
BAYLEYEGN Masreshaw	Allocataire UPSud, defended December 2012, Post-Doc Boston
CHAMTOURI Maha	Cotutelle avec U Tunis, defended May 2013
FISZMAN Nicolas	Bourse thèse CNRS conjointe INP-INSB, October 2010 -
SEREDA Alexandra	CIFRE HORIBA, October 2011 -
FEDERICI Antoine	Allocataire U-PSud,October 2012-
SARKAR Mitradeep	Allocataire IDEX Paris-Saclay, October 2012-

Visiting scientists and post-doctoral fellows

BARBILLON Grégory	Post-doct ATER Sept 2009 – August 2010
CHOMMY Hélène,	Post-doc November-December 2012 (financement ANR)
DUVAL Aurélien	Post-doc August 2009 – December 2010, chercheur vacataire Canada
GREBENUYK Anton	Oct 2012 - déc 2012, then a doctoral student atSaratov University (Russia)
GUROV Igor	Head of the Optics department at ISMO, Saint-Petersbourg (Russia)
KONISHI Tsuyoshi	Chercheur invité, Osaka University, Japan (2009-2010)
MAKHLOUF Houssine	Post-doc October 2011 - March 2012
RODRIGUEZ-OTAZO Mariela	guest scientist January - March 2013 (RTRA-triangle de la physique)
ROY Maitreyee	guest scientist, National Measurement Institute, West Lindfield, Australia (2 wk 2008)
SPADAVECCHIA Jolanda	Post-doc de May 2006 - October 2009, actuellement CR CNRS
VISSCHER Koen	Univ. Tucson, USA, 6 months (2009-2010) (UPSud, CNRS)
WALBOTT Hélène	Post-doc March 2012 - March 2013 (financement ANR)

Engineering support

The group benefitted considerably from the engineering support staff, and in particular Alain Aide, draftsman, and Alain Bellemain and Gisèle Roger, instrumentation engineers. It interacted as well with all research engineers in the instrumentation, lasers, technology, and scientific computing support staff.

Master level trainees (for at least 3 months)

KOKHANOVSKY Alexey, M1, 2013
DE TOLDI Eliot, M1, 2013
SIRET David, M1, 2013
GILLANT Flavie, M2, 2013
COMTET Jean, X3, 2012-2013
FEDERICI Antoine, M2, 2012
DELLA VALLE Cécile, X3, 2011-2012
VAZQUEZ-FACI Tania, M2 (ENS Cachan), 02-07/2012
SARKAR Mitradeep, M1, 2011
SASHALA NAIK Alvin, M1 2011
MU Cong, M1, 2010
SIVANKUTTY Siddharth, M2, 2010
BRZEZINSKI Michal, M1, 2009
M'ZAH Abir, M2 Math et informatique, 2009
BAYLEYEGN Masreshaw M2, 2009
OUISSA Ghizlane, M2 Bio-ingénierie 2008
REHBINDER Jean, X4, 2008

(In addition, about ten short term interns were hosted in the group).

1. SCIENTIFIC REPORT

The Biophotonics group conducts its research activity at the interface between photonics and biochemical/biomedical applications. It holds and develops an expertise in optical coherence tomography (OCT), high-resolution fluorescence microscopy, optical tweezers and plasmonics imaging, with a constant concern about applications. Close collaborations with biologists, chemists and hospital doctors address applications ranging from fundamental studies of ribosome dynamics to optical biochips and to ophthalmology, neurology and atherosclerosis. Our goal is to "advance the frontiers" of photonic characterization systems in relationship with actual biochemical issues.

The Biophotonics group was recently created, as of July 2011. It brought together three teams that were already part of Laboratoire Charles Fabry, from the groups "Laser and Biophotonics" and "Atom Optics". These teams shared scientific interests including strong interactions with biochemists, biologists and medical doctors. The new group provides a clearer image of our activities in the fast-growing field of biophotonics, both towards our colleagues of the scientific community as well as towards the increasing number of students interested in this field. We are involved in the development of new graduate courses in biophotonics, and participate in the structuration of research at the interface between physics and biology in the Plateau de Saclay area, as well as taking part in outreach activity towards a broader public. Over this period, the group has been representing CNRS and IOGS as the French core-founding member of the European Network of Excellence in Biophotonics, Photonics for Life, P4L, Networking for better Health Care.

The Biophotonics group consists of 5 permanent researchers, and about the same number of PhD students and visitors. To achieve our goals we also benefit from close collaboration with the simulation and clean room facilities, namely Mondher BESBES, Anne-Lise COUTROT and Buntha EA-KIM, as well as support from instrumental engineering, namely Florence FUCHS and Sylvie JANICOT. The present structure of the group, and consequently that of the following scientific report, still reflects the activities of the three teams, namely "NanoBioPlasmonics", "Biomedical Imaging Systems" and "Single Molecule Biophysics". Noticeably, in the course of those last two years, interactions within the new group has already led to new projects based on shared expertise, such as the combination of optical tweezers and optical coherence tomography to study the mechano-transduction of endothelial cells in the context of atherosclerosis.

In this report, we will present the current group activities, organized in three subsections: "NanoBioPlasmonics", "Biomedical Imaging Systems" and "Single Molecule Biophysics" corresponding to the former constituting teams, which covers most of the reporting period. For each one of them we will point out our important results in the areas of instrumentation, photonics and bio-applications, our focus being always on designing innovative optical systems to address open bio-applications issues. We will also emphasize hereafter a few key collaborations as well as the most significant publications.

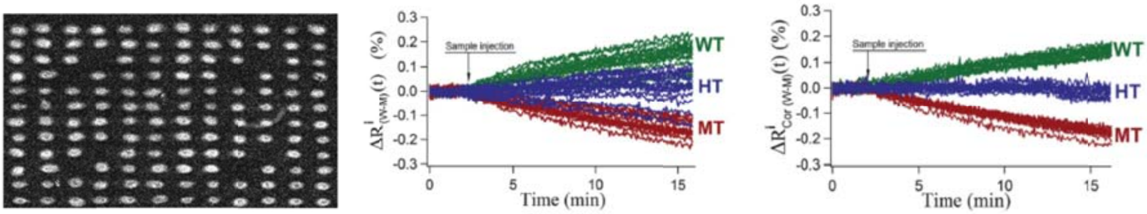
A. "NANOBIOPLASMONICS"

The plasmonic sensing activity covers three main subfields, namely "plasmonic instrumentation", "plasmonic structures" and "plasmonic sensing applications".

Our work in "**plasmonic instrumentation**" (PhDs of Aurélien Duval, Mohamed Nakkach and Alexandra Sereda, main collaboration with Horiba Jobin Yvon) has involved increasing the field of measured parameters. Typically, imaging sensors such as those used for biochip reading, record the evolution as a function of time, t, of a surface, with 2D coordinates, x and y. The reflectivity of the surface is conveniently measured in those systems, as it does not require any moving parts, and therefore the measured data consist of R(x, y, t). We have progressively added the coupling parameters, angle θ and wavelength λ, the direction of propagation and therefore of polarization P, and recorded as well a conventional microscopy image, I (from above the sample). The total field of data therefore consists in R(x, y, t θ, λ, P) and I(x, y, t). In particular, part of this work was published in 2009 [Bardin *et al.* BioSensors and BioElectronics 2009] in a configuration using a white light source and imaging the spectra of a 1D array of bio-relevant spots. The sensitivity we had demonstrated was later referenced as one of the best achieved, close to the theoretical limit that can be achieved using classical propagating plasmons [Piliarik and Homola, Optics Express 2009, *"Surface Plasmon Resonance (SPR) Sensors: approaching their limits?*]. This latter point is one of the reasons for which we initiated during this period our work on new plasmonic structures as explained further. Our results in this field led to a specific collaboration with one of its major industrial actors, namely Horiba Scientific, Jobin Yvon. We are investigating how to use some of the supplementary data in a routine manner able to give access to **more precise and reliable biomolecular interaction information**.

Recently, at the beginning of the period covered by this pluri-annual report, we started **investigating new plasmonic structures**, both theoretically and experimentally (PhDs of Maha Chamtouri and Mitradeep Sarkar, Post-doc of Gregory Barbillon). This was achieved through many collaborations, internal, national and international (main collaboration with Duke University, New Delhi Institute of Technology in India, Universities of Montreal and Sherbrooke in Canada, Institut d'Electronique Fondamentale Orsay). Our goal in this area is, firstly, to better understand the intermediate regime between the "classical" propagating plasmons on a semi-infinite flat interface and the "classical" nanoparticles in solution, and, secondly, to demonstrate structures that would clearly enhance some of the targeted application figure of merit. This is achieved studying both the nano and micro-structure size domains. On the one hand, mainly through internal LCF collaboration, we have **enhanced our simulation capabilities**, continuously gaining computation time and precision, allowing exhaustive parameter investigation of 2D structures, from nano up to micro [Chamtouri et al., Plasmonics 2013], and more recently from 2D to 3D [Sarkar *et al.* 2013]. On the other hand, through internal, national and international collaborations we have used our set-ups to also **characterize experimentally** different structured samples [Dhawan et al., Nanotechnology 2011].

Concerning the **plasmonics applications** (PhDs of Jérôme Hottin, post-docs of Jolanda Spadavecchia, main collaboration with Hopital Henri Mondor de Créteil, Centre de Génétique Moléculaire de Gif sur Yvette, GenOptics), we have historically focused on DNA:DNA interactions with applications to medical genotyping (in collaboration with Michel Goossens et al, from Hospital Henri Mondor, on the specific case of Cystic Fibrosis, *CF*, (mucoviscidose) , the most common genetic illness that affects 1/4000 individuals. A recent paper [Hottin *et al,* Analyst 2012] uses this application example to demonstrate a **self-calibration methodology** that can be used to take into account inherent spatial heterogeneity in biochip functionalization and significantly increase data precision. This later point is illustrated in the figure below, showing genotyping discrimination of the three possible SNP (Single Nucleotide Permutation) genotypes, without and with this self-calibration methodology, which we, with CNRS, had previously patented.



Example of biomedical application result: the three possible genotypes concerning a cystic fibrosis mutation (Wild Type, Mutated Type, Heterozygote Type) were evaluated using our SPRI (Surface Plasmon Resonance Imaging) system – its accuracy, using a self-calibration methodology (right), allows unambiguous discrimination of the three possible cases.

Perspectives:

These three activities in Bioplasmonics have led us to constitute a consortium[6], 5 academic partners and an industrial one, to tackle in the following four years 2013-2016, with ANR funding, the demonstration of a nano-micro-plasmonics based **dual system** capable of both quantification by **SPRI** and identification by **SERS** of binding events on dedicated biochips. Main investigated applications concern early cancer diagnosis through detection of specific markers at trace level and food quality and safety through analysis of trace contaminants.

B. "BIOMEDICAL IMAGING SYSTEMS"

This team works on new imaging and optical microscopy techniques to meet specific needs in the biomedical field. Our activities, concerning both technological and theoretical aspects, are carried out on two sites, IOGS and Centre de Photonique Biomédicale (CPBM) of Université Paris-Sud. Our main collaborations are: Laboratoire d'Optique Appliquée ENSTA (K. Plamann), ISMO (S. Lévêque-Fort, G. Dupuis), Institut du Cerveau et de la Moelle de l'hôpital Pitié-Salpêtrière (M.C. Pottier), Laboratoire de Mécanique des Solides de l'École Polytechnique (Jean-Marc Allain), IMNC-IN2P3 (Frédéric Pain), Saratov State University Russia (A.Grebenuyk), Institute of Photonic Technology Jena (J. Popp), Lund University Hospital Sweden (K. Swanberg).

We are pioneers in an alternative technique to conventional OCT, termed **Full-Field OCT** (FF-OCT). Based on white-light interference microscopy, FF-OCT produces *en-face* tomographic images using an area camera and illuminating the whole field to be imaged with low-coherence light. The major interest of FF-OCT lies in its high

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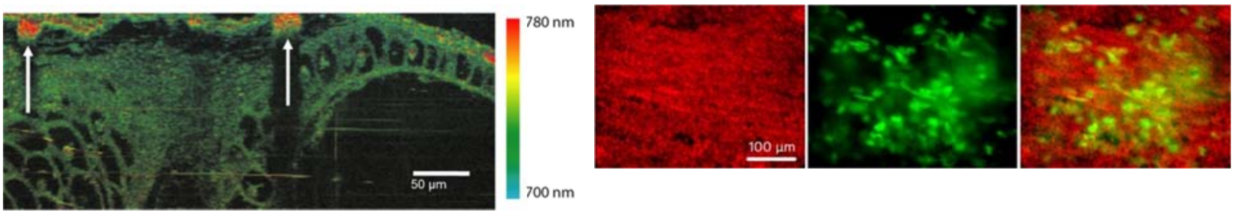
[6] The consortium is initially constituted of Laboratoire Charles Fabry as coordinator, laboratoire Chimie, Structures, Propriétés de Biomatériaux et d'Agents Thérapeutiques CSPBAT, Institut d'Electronique Fondammentale IEF, Institut des Nanotechnologie de Lyon INL and AgroParisTech as academics partners as well as Horiba Jobin Yvon as industrial one. A users club that already counts several medical institutions, CHUs, is expected to grow in the final two years of the project. Nearly 600 person.month effort will be dedicated to this project.

imaging resolution (1 µm), far higher than the resolution of conventional OCT. Morphological images of biological tissues close to histology images can be produced without any preparation. This work led to the foundation in 2008 of the LLTech Company, which sells this technology for biomedical applications (2 CNRS licences). We have recently proposed several extensions to the FF-OCT technique to enhance the image contrast, making differentiation of distinct tissues easier (PhD of D. Sacchet and A. Federici). Substantial efforts have been done for achieving *in vivo* imaging [Appl Opt 45, 1480 (2010)]. Images can be acquired simultaneously in two distinct spectral regions, centered at 800 and 1200 nm [Opt Express 16, 19434 (2008)]. The spectrum of light backscattered by the sample can be measured at any point by Fourier analysis of the interferometric data, to provide spectroscopic information [Opt Express 16, 17082 (2008)]. Polarization-sensitive FF-OCT produces images with both intensity-based and linear-retardance-based contrasts, thus providing additional information related to the sample polarization properties. [Opt Express 20, 9962 (2012)]. FF-OCT and optically sectioned fluorescence microscopy have been implemented in a novel dual modality instrument: FF-OCT shows the tissue micro-architecture, while fluorescence microscopy highlights specific tissue features with cellular-level resolution by using targeting contrast agents. Complementary tissue morphology and biochemical features could potentially improve the understanding of cellular functions and disease diagnosis. [Opt Letters 37, 1613 (2012)]. In collaboration with theorists from Saratov University (Russia), we have developed a frequency-domain FF-OCT system for 3D image acquisition with unprecedented spatial resolution.



Left: Combined intensity/spectroscopy FF-OCT image of a Xenopus embryo (in vitro). The center of mass of the power spectrum of light detected from each point of the sample is used as the spectroscopic metric encoded in color. White arrows indicate the presence of melanocytes.
Right: FF-OCT image and optically sectioned fluorescence image in pseudo-colors of mouse colon stained with Acridine Orange. The fluorescence information (green) reveals individual cell nuclei, while the FF-OCT data (red) shows a fibrous pattern that corresponds to the connective tissue.

We also work on conventional scanning OCT. In particular, we have developed a **Spectral-domain OCT** (SD-OCT) system at 1.3 µm center wavelength using a broadband light source consisting of two multiplexed superluminescent diodes (PhD of M. Bayleyegn). The spectral region around 1.3 µm is optimal for its reduced absorption and low tissue scattering, in order to maximize the imaging depth. The system has an axial resolution of 2.8 µm in tissues, which is the best resolution ever achieved with this technology at this wavelength. In particular, we have demonstrated the possibility of imaging the Schlemm's canal inside the human eye suffering from glaucoma. This paves the way to using SD-OCT for guiding glaucoma laser surgery, which would represent a significant progress in **ophthalmology** [Optics Com 285, 5564 (2012)].

Our research activity at CPBM concerns **high-resolution fluorescence microscopy**. The diffraction-limited spatial resolution of a microscope can be exceeded by using Stimulated Emission Depletion (STED) microscopy. The principle, proposed in 1994, is to illuminate with a laser on the outskirts of the fluorescence spot induced by another focused laser beam to depopulate the excited state by stimulated emission and thus prevent the fluorescence to occur at this location. It is thus possible to reduce the effective size of the fluorescence spot to less than 50 nm. We have developed a tunable **STED microscope** capable of exciting a wide range of fluorophores (PhD of V. Devauges). The fluorescence measurement can be performed in a time-resolved manner to access the fluorescence lifetimes.

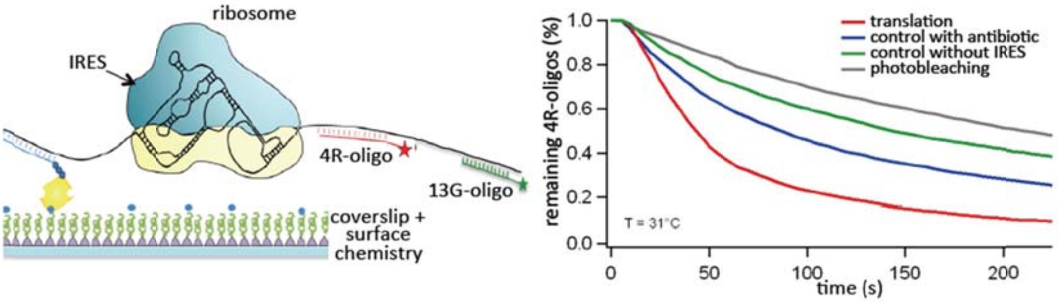
Perspectives:

Research will still be carried out on FF-OCT to achieve *in situ* ultrahigh-resolution imaging with improved detection sensitivity of diseased tissues. The possibility to perform endoscopic imaging will also be investigated. Several complementary imaging modalities will be coupled to FF-OCT including nonlinear optical microscopy and elastography; an optical tweezer system will also be combined to FF-OCT. Our STED microscope will be devoted to applications; this technology will definitely open new perspectives in the study of many biological processes, up to now inaccessible due to insufficient spatial resolution, especially in neurobiology for Alzheimer's disease.

C. “SINGLE MOLECULE BIOPHYSICS”

This team focuses on studying dynamical aspects of biological processes using **optical tweezers** and single molecule **total-internal reflection fluorescence microscopy** (TIRFM). TIRFM allows **co-localizing** different labeled biomolecules, while tweezers are used to **exert and measure forces** in the 1-100 pN range.

Photophysics of organic fluorescent probes in relation with the study of ribosome: Bodipy-Fl is a small marker used in the commercially available Bodipy-Fl-labeled lysine charged transfer RNA for in vitro translation experiments. However, Bodipy-Fl has poor photophysical properties to be used in single molecule experiments. We used a ROXS system (for **Reducing and Oxidizing System**)[7], to improve its photostability. Buffers are usually depleted in oxygen, the main agent of photobleaching. However, oxygen also quenches the dye's dark state. Its removal therefore stabilizes the dark state and reduces the fluorescence rate. Tinnefeld’s team replaced oxygen with oxidizing and reducing species to quench the triplet state via charge transfer reactions. In collaboration with G. Clavier and R. Méallet-Renault (PPSM, ENS Cachan), we developed a ROXS adapted to Bodipy-Fl and demonstrated **x20 increase** of the total number of photons emitted before photobleaching by a single Bodipy-Fl, with almost no loss on the fluorescence rate [ChemPhysChem, **12**, 1657 (2011)]. We also adapted **ROXS to the use of the cell extracts** available in commercial translation kits. The results on the ATTO-647N dye are good in PURE-System (x5 gain), but not in rabbit reticulocyte lysate (RRL) (max x3 gain, unstable in time), probably due to its high oxygen content.



Single Ribosome translation experiment - Left: Initiation complexes are attached specifically to a coverslip, and located thanks to the fluorescently-labeled oligonucleotides (4R and 13G-oligos). Right: kinetics of translation, and controls (antibiotic blocking partially the ribosome, mRNA without IRES – thus no complexed ribosome -, and photobleaching)

Translation kinetics of single eukaryotic ribosomes: D. Dulin, A. Le Gall, N. Fiszman and H. Chommy took part to this work done in close collaboration with Olivier Namy (Institut de Génétique et Microbiologie, U-PSud), expert on eukaryotic translation. We measure the kinetics of translation with TIRFM using the ribosome helicase activity[8] (cf. Figure above). Labelled oligonucleotides are hybridized along the mRNA downstream IRES (Internal Ribosome Entry Site), a specific secondary structure allowing the ribosome initiation without additional factors. As the ribosome translates a codon protected by an oligonucleotide, it unwinds the duplex and the fluorescence signal disappears. We measured two characteristic times for single ribosome translation activity: a fast one (typ. 1s) representative of one elongation cycle and a slow one (typ. 40s) showing that the ribosome needs more time to perform fthe first elongation step due to the IRES hindrance. These are to our knowledge the **first results concerning single-molecule eukaryotic elongation**, and are the object of an article in preparation. We are also using this methodology to study various kinetics aspects of translation, through collaborations with other teams of biologists (D. Fourmy, Centre de Génétique Moléculaire, C. Giglione, Institut des Sciences du Végétal, ANR project Ribodyn). This original yet conceptually simple method opens the way to many studies of ribosome dynamics, in particular the highly interesting question of ribosome frameshifting.

Novel methods for calibrating optical tweezers: This work was done during A. Le Gall’s thesis in collaboration with K. Visscher, professor invited in our team. Usual optical trap calibration methods rely on the analysis of the trapped bead motion power spectrum density, measured with a 4-quadrant photodiode (QPD). This requires also a delicate QPD-signal calibration. We developed a rapid and simple method for a **complete calibration of the trap in one step** [Optics Express **18**, 26469 (2010)]. An acousto-optic deflector (AOD) quickly moved the trap, while the bead, which has a slower response time, returns to the trap center with a delay that gives us a measurement of the stiffness of the trap. The amplitude of the trap deviation with the AOD is accurately measurable.

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[7] Vogelsang et al, Angew. Chem. Int. Ed., **47**, 5465 (2008)

[8] Takyar et al, Cell, **120**, 49-58 (2005)

It gives a direct calibration of the QPD signal in nm. We are currently working on another calibration method using the Bayesian inference theory, requiring much less experimental data points, in collaboration with A. Alexandrou (Laboratoire d'Optique et Biosciences, Polytechnique).

Mechanotransduction in endothelial cells: We are combining our expertise on optical trapping with the one of A. Dubois on OCT to study, in collaboration with A. Barakat (Laboratoire d'Hydrodynamique, Polytechnique), the effect of force transduction on blood vessels endothelial cells. Optical tweezers are used to exert a force, constant or oscillating, well characterized, both in amplitude and direction. We then monitor the morphological changes of the cell nucleus by OCT that we will combine with the optical tweezers to give a 3D image of the deformed nucleus. This project has started recently and is enriched by a new collaboration with N. Hildebrandt (IEF, U-PSud), expert in Förster Resonance Energy Transfer, to monitor molecular conformation changes. We will follow a genetically encoded force-transduction reporter in order to prove whether the force transmission is mediated by the cytoskeleton or by chemical reactions.

Perspectives:

Our breakthrough on single eukaryotic ribosome dynamics opens the way to studies of many processes affecting translation, such as premature stop codons or frameshifting, in close collaboration with teams of biologists who are actually merging in a large biology institute in Gif/Yvette. In parallel, our expertise on optical tweezers, combined with FRET and OCT, all through collaborations both inside the group and in the Plateau de Saclay area, will give us a multimodal approach to mechanotransduction studies on endothelial cells, which would lead to a better understanding of cardiovascular diseases.

2. Reputation and academic attractivity

Grants and human resources: The group has obtained 20 research grants including 4 from the ANR (Agence Nationale pour la Recherche), and coordinated 75% of them. All these grants imply teams of physicists and biologists, chemists or hospital doctors. Specific funding for salaries was raised for 14 PhD students (including 4 international students and 3 industry-funded), 6 post-docs and 5 invited foreign researchers. M. Canva spent one year in 2009-2010 at the Fitzpatrick Institute for Photonics at Duke University (USA) as invited researcher.

The group is actively involved in **scientific networks:**

- 2 Labex (Laboratoire d'Excellence): NanoSaclay ("emergence" grant received in 2013 and member of the flagship "nanophotonique") and PALM (member of the graduate education committee).
- LUMAT federation (2 grants), and PRES UniverSud (2 grants)
- 3 GDR *(Groupement de Recherche)*: « Ondes », « Or-Nano », and « PMSE (Plasmonique Localisée Spectroscopie Exaltée) ».
- Representative of CNRS and IOGS as French core-founding member of the European Network of Excellence in Biophotonics.
- 2 LIA (*Laboratoire International Associé / CNRS)*: Tunisie (Tunis) and Canada (L2N Sherbrooke).

Expertise: participation in PhD / HDR committees, many as "referee" or president ; reports for funding agencies / article reviewing.

Conference organization: Scientific committee of BIOS, SPIE Optics & Photonics, Interferometry XVI: Techniques and Analysis, Plasmonic in Biology and Medecine, Conference of Young Biomedical Engineers and Researchers, International Topical Meeting on Optical Sensing and Artificial Vision, Horizons de l'Optique, C2I

3. INTERACTION WITH THE SOCIAL, ECONOMIC AND CULTURAL ENVIRONMENT

The group has strong **industrial collaborations**. It coordinates since 2013 the ANR project PIRANEX involving Horiba Scientific, has transferred 2 patents to the start-up LLTech, and is involved in the C'Nano valorization committee. It has also obtained 3 CIFRE (industrial) grants for its PhD students.

The group belongs to 2 Doctoral Schools (**Écoles Doctorales** STITS - Sciences et Technologies de l'Information des Télécommunications et des Systèmes - and EDOM – Ondes et Matière) and participates in the new structuration of doctoral schools within the University Paris-Saclay, in particular the new EOBE (Electrical, Optical and BioEngineering) school.

All group members (including CNRS researchers) **teach** in different places, especially in Master programs that are joint between several institutions. They develop many new courses at the physics/biology interface that aim at expanding and federating the teaching offer in this field.

The group participates in **outreach activities** such as "fête de la science", summer schools for PhD students or secondary school teachers, and wrote a popularization article in Techniques de l'Ingénieur.

4. Conclusions and perspectives

The Biophotonics group, with its current 5 permanent members, has been very active over the past four and a half years, publishing mainly experimental but also some theoretical work. Achievements include the demonstration of optical systems working at the current limits of the state-of-the-art, as well as participation in life science research using our instruments especially optimized towards this goal. Most of these results have been achieved through close collaborations with colleagues of other fields.

Since the creation, in July 2011, of the Biophotonics group, more and more is being shared, technically and scientifically between the members. A few examples include a new chemical room facility, shared lab space, regular group meetings, a recent joint publication between researchers of different teams within the group, and a new joint experimental setup merging optical tweezers and OCT to allow more complete cell characterizations. We have recently attracted several good doctoral students and this, together with the recent funding of projects, will allow us to achieve the goals we target in the years to come.

LASERS

LASERS GROUP MEMBERS

Head: *GEORGES Patrick, Directeur de Recherche, CNRS*

Faculty and Research Faculty holding permanent position:

BALEMBOIS François	Professeur des Universités
DRUON Frédéric	Directeur de Recherche, CNRS
HANNA Marc	Chargé de Recherche, CNRS
LUCAS-LECLIN Gaëlle	Maître de Conférences IOGS/U. Paris-Sud

Industrials collaborators involved in the common research laboratories:

MARTIAL Igor	Research Engineer from Fibercryst
ZAOUTER Yoann	Research Engineer from Amplitudes Systemes

Doctoral students:

BOUDEILE Justine	Allocataire, graduated 2008	Teacher
BLANDIN Pierre	BDI CNRS, graduated 2008	Assistant professor
COCQUELIN Benjamin	BDI CNRS/CNES, graduated 2009	Engineer LSC & SGCC
STEINHAUSSER Bastien	DGA, graduated 2009	Engineer Thales Optronique
CASTAING Marc	CIFRE Oxxius, graduated 2009	Engineer Azur Light Systemes
PABOEUF David	DGA, graduated 2009	Post-doc Univ. of Strathclyde
SANGLA Damien	Allocataire, graduated 2009	Engineer Eolite Systemes
PAURISSE Mathieu	DGA, graduated 2010	Engineer Amplitude Technologies
MORIN Franck	BDI CNRS, graduated 2010	Engineer Amplitude Systemes
MARTIAL Igor	CIFRE Fibercryst, graduated 2011	Engineer Fibercryst
BLOOM Guillaume	CIFRE Thales RT, graduated 2012	Engineer Thales Optronique
DANIAULT Louis	Allocataire, graduated 2012	Post-doc Lab. Optique Biosciences
RICAUD Sandrine	CIFRE Amplitude Syst. graduated 2012	Engineer Thales Optonique
RAMIREZ Patricia Lourdes	Allocataire, graduated 2013	Post-doc LULI

DELEN Xavier	DGA/CNRS since Sept 2010	*(Single crystal fibre amplifiers)*
AUBOURG Adrien	CIFRE Fibercryst since May 2011	*(Er:YAG ns eye-safe lasers for active imaging)*
DEYRA Loïc	DGA since Oct 2011	*(UV generation by nonlinear conversion)*
FRIEBEL Florence	Allocataire since Nov 2011	*(High energy Yb:CaF_2 multipass amplifiers)*
LEVEQUE Louis	BRIDLE FP7 since Oct 2012	*(Coherent combining for high power diodes)*
GUICHARD Florent	CIFRE Amplitude Syst. since Dec. 2012	*(Coherent combining fs fibre amplifiers)*
POUYSEGUR Julien	CIFRE Amplitude Syst. since Mar. 2013	*(New Yb doped crystals for fs amplifiers)*

Visiting scientist and post-doc fellows:

JIANG Shifeng	Post-doc, ANR CAN (Sept 2008 - May 2010)
PAPADOPOULOS Dimitris	Ingénieur Recherche LULI/Polytechnique, projet Apollon (July 2008 - July 2012)
PELLEGRINA Alain	Ingénieur d'Etude LULI/Polytechnique, projet Apollon (Oct. 2009 - Oct 2013)
CAMARGO Fabiola	Post-doc, DGA Chamsin and Lamparo, RTRA Lasomono (Sept 2010 - Oct 2013)
GOZHYK Iryna	Post-doc, RTRA Power852 (Nov 2012 - April 2014)
WECHELT Birgit	PhD student from IFSW Stuttgart (Dec 2010 - Feb 2011)

Engineering support

The group benefitted considerably from the engineering support staff, and in particular Sylvie Janicot and Gérard Roger, laser instrumentation engineer.

Master level trainees (for more than three months)

BARRIENTOS BARRIA Jessica	*IOGS 2A and 3A 2009-2011 (learning period 50% in the Laser group)*		
TEYSSEIRE Raphael	*M1 IFIPS UPSud 2008*	DOURI Nouri	*M1 IFIPS UPSud 2008*
FRIEBEL Florence	*Diplomarbeit 2008*	MARTIAL Igor	*IOGS 3A 2008*
GHOSH Sougata	*M2 Erasmus Mundus 2009*	SUN Xiaoyu	*M2 Erasmus Mundus 2009*
BRZEZINSKI Michal	*M1 Erasmus Mundus 2009*	ABD ALRAHMAN Chadi	*M2 OMP 2009*
DELEN Xavier	*IOGS 3A 2010*	BAI Lu	*M1 Polytech PSud 2011*
ZAGORIANOU Maria	*M1 Erasmus Mundus 2011*	DONG Renxing	*M2 PON 2012*
VAN DE WALLE Aymeric	*IOGS 3A 2013*	DUMONT Paul	*IOGS 3A 2013*
BARBET Adrien	*IOGS 3A 2013*		

(and 9 one-month internship students from the Institut d'Optique – Graduate School)

1. SCIENTIFIC REPORT

The research activity of the Lasers group concerns the development of new **diode-pumped solid-state lasers** covering a broad range of gain media (crystals, fibres, semiconductors), temporal regimes (from CW to femtosecond) and wavelengths from the UV to the infrared. Based on our **deep understanding of the physics of lasers and nonlinear optics**, we enhance the properties of lasers and extend their range of applications (eye surgery, high intensity physics, micro-machining). During the last five years, we have studied novel architectures for thermal management (single crystal fibre, thin disk), high energy femtosecond amplification (regenerative and multipass amplifiers) beam quality improvement (spatial and temporal coherent combining), few cycles pulses generation (optical parametric chirped pulse amplification), optically-carried microwave signal generation (dual frequency oscillators) and new wavelengths generation. Within the Paris-Saclay area, we play a key role in the laser research field since we are responsible for the development of the **Front-end for the Apollon 10 PW (10^{15} W)** laser facility (currently the only laser in the world at this level of peak power) funded by the current CPER (Contrat Plan Etat Région) and the **Equipex CILEX**.

It is noteworthy that the Lasers group position is singular in the French Research panorama: we are the only research group covering such a broad activity in the physics of lasers and laser sources development. With 21 PhD students over the five last years (7 are currently working towards their diploma), we have developed a significant task force to carry out multiple research projects covering many fields of today research on laser sources and applications. While maintaining a high academic scientific level, the Lasers group has also developed strong links with many French laser companies. Since 2008, 7 PhD students (among the 21) were (or are currently) funded by CIFRE contracts involving an industrial partner. With **Amplitudes Systemes and Fibercryst**, we have enhanced the collaboration by establishing two **common research laboratories** with joint research projects and PhD students supervised by researchers from the Laser group and a research engineer from the company.

Our research activity is not only dedicated to the development of lasers, it has also strong links to applications. For example, we developed a ps fibre laser for the early detection of prostate cancer based on biopsy assisted by fluorescence and ultrasound multimodality imaging within an ANR TecSan project lead by CEA Grenoble. We also worked on a new 1.6 µm fs µJ fibre laser source for corneal surgery funded by an ANR TecSan project.

A. Summary of the research activities

A.1 Single crystal fibre

Single crystal fibres (SCF) are **long and thin crystal rods** (typical length 50 mm and diameter below 1 mm). Their geometry allows excellent heat management and pump confinement through total internal reflection (fig 1a). This new concept for high power laser was discovered by the Lasers group and protected with **3 patents held by CNRS and Fibercryst**. Since 2008, the Lasers group had an intense activity on SCF: Nd:YAG (at 946 nm and 1064 nm [Deyra APB 2013]), Er:YAG (1645 nm, [Aubourg OL 2013]) and Yb:YAG (1030 nm) SCF were explored in parallel (DGA Minitelia, Chamsin and Newmat, ANR Idealaser). Our work brought a significant breakthrough in terms of laser oscillator performance with 250 W CW output power at 1030 nm [Delen OL 2012] (fig 1b). In the pulsed regime (ns to fs), we demonstrated that SCF amplifiers (fig 1d) are able to boost fibre laser performance (which are generally limited by non linear effects such as Raman or Brillouin scattering) by one order of magnitude [Martial OE 2011, Delen OL 2013-1]. Our research activity on SCF has opened new possibilities for laser sources **combining high peak power and high average power**: as much as 1 mJ, 380 fs pulses have been obtained at 10 kHz from an Yb:YAG SCF amplifier [Delen OL 2013-2].

It is noteworthy that scientific, technological and industrial developments have been successfully carried out in parallel. The Lasers group works with the company **Fibercryst** since 2003, and since 2012 in a common research laboratory. Our research on SCFs has strongly reoriented Fibercryst's activities. With the launch of the Taranis product (fig 1c) in 2011, our close collaboration has resulted in a significant market value (turnover 200 k€ in two years and 500 k€ targeted in 2013) and it has triggered many triangular collaborations including other French laser industrials such as **Cilas, Teem Photonics, Amplitude Systemes and Eolite Systems**.

SCF is now recognised as a new laser technology that can compete with, or complete well-established technologies like thin disk lasers and slab lasers. However, the potential of SCF for high power amplifiers has just started to be revealed: the pump power limit that can be sustained by the **SCF technology is estimated at 1 kW**. We plan to explore high repetition rate (1-20 MHz) SCF amplifiers for picosecond (1-5 ps) and femtosecond pulses with a target average power in the 100 W range within the **recently accepted European project RAZIPOL** (starting in Nov. 2013). The excellent thermal management and low depolarization losses in SCF will be fully exploited with radial and azimuthal polarized beams which are very promising **to increase the quality and speed of material processing**. Moreover, to boost the power one step further, we will develop SCF amplifiers based on passive coherent combining within a Sagnac loop, a concept recently demonstrated by the Lasers group with rod-type fibers. We plan also to explore SCF geometry with other crystals than Yb:YAG: namely Yb:CaF$_2$ or Yb:CaGdAlO$_4$

(Yb:CALGO), which have broader emission bandwidth than Yb:YAG and therefore the potential to produce shorter amplified pulses.

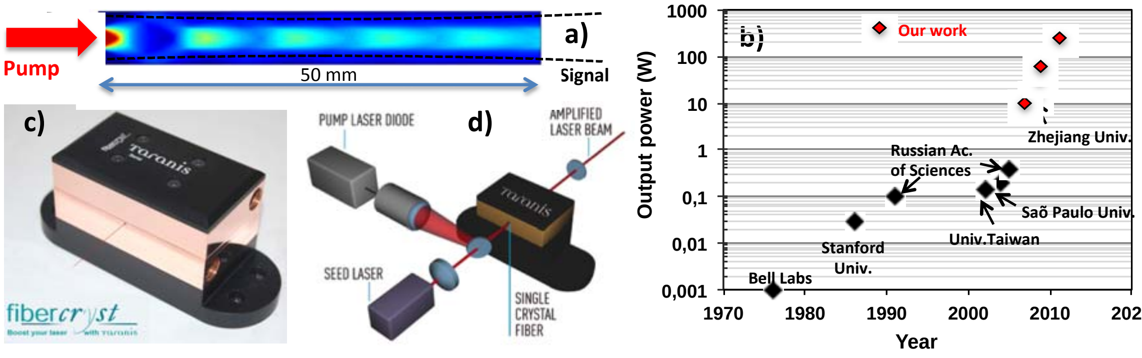
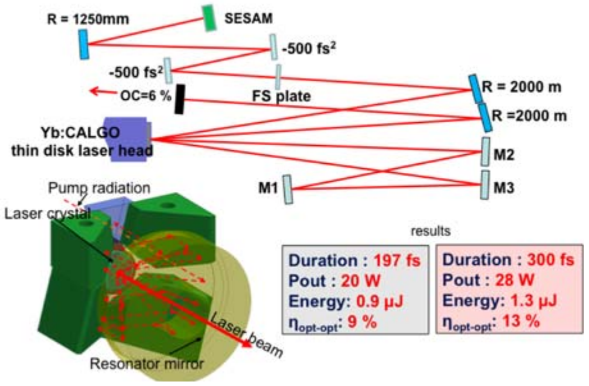


Fig. 1: (a) pump beam propagation through a SCF confined in the fibre center by cylindrical symmetry, (b) output power versus years for SCF oscillators, (c) TARANIS module commercialized by Fibercryst, (d) Typical implementation of SCF amplifier.

A.2 Ultrafast lasers

The generation of femtosecond pulses from solid-state diode-pumped laser systems at high power / energy levels represents an important trend in the field of lasers, with an ever increasing number of applications in the industrial world, such as high repetition rate material processing, and also for the scientific community. The Lasers group is one of the major players in this area, both in systems based on bulk gain material and in fibre lasers. Since five years we have developed a **strong partnership with Amplitude Systems** through **a common research laboratory**.

Bulk crystal based femtosecond laser sources:



Duration : 197 fs Pout : 20 W Energy: 0.9 µJ $\eta_{opt-opt}$: 9 %	Duration : 300 fs Pout : 28 W Energy: 1.3 µJ $\eta_{opt-opt}$: 13 %

Fig. 2 : fs thin-disk oscillators made with Yb:CALGO

For more than a decade, the Lasers group has been recognized as an **international leader** in the research involving new ytterbium doped crystals for the development of femtosecond high-power lasers and amplifiers. This leadership has been possible thanks to a strong relationship with our partners: two French laboratories experts in crystallogenesis: **the LCMCP (Chime Paris) and the CIMAP (Caen)** and the company **Amplitude Systemes**. During the past five years, the Lasers group has reinforced his position on this subject by coordinating projects with these partners (ANR Femtocryble). The goal is to realize the next generation of femtosecond laser chains. In order to combine the ability of producing energetic ultrashort pulses at high repetition rate, work has been concentrated on broadband fluorescence Yb:CaF$_2$ and Yb:CALGO crystals presenting high thermal conductivity. These crystals, that are now recognized and intensively used by the laser community, have indeed been discovered by the Lasers group / Chimie Paris partnership in 2003-2004. We peformed the fundamental laser parameters study and optimization in order to use these crystals in high-power and/or high-energy novel laser architectures.

Stability issues in passively mode-locked oscillators related to crystal properties have been studied [Friebel OL 2009, Papadopoulos OL 2009]. **Regenerative amplifiers** based on Yb:CaF$_2$ and Yb:SrF$_2$ have also been demonstrated, establishing the state of the art for short pulse high-repetition-rate Yb-doped-based amplifier (sub-180 fs pulses at the mJ level and 1 kHz repetition rate [Ricaud OL 2010-1]).

The development of Yb:CaF$_2$ laser at **cryogenic temperature** has been performed for the very first time establishing, firstly, the highest power and efficiency ever obtained with this crystal, but also allowing the unique **unveiling of an unknown laser line at 992 nm** with a very low quantum defect for Yb-doped crystals (patent with Amplitude Systemes, Ricaud OL 2010-2). This work is embedded in the APOLLON 10PW laser project (see section 2.3 below) whose front-end is developed by the Lasers group. This front-end includes novel high-energy amplifiers based on Yb doped crystals, thus is strongly connected to the research involving new crystals made in the Lasers group. Within this work, unprecedented **high-energy multipass amplifiers** with Yb:KYW (27 mJ at 100 Hz) and

$Yb:CaF_2$ (160 mJ at 20 Hz) have been demonstrated [Papadopoulos OL 2011]. Further work will be pursued to reach the Joule energy level at 10's Hz repetition rate from these new $Yb:CaF_2$ based multipass amplifiers.

Thin disk femtosecond oscillators:

We develop ultra-high power short pulse oscillators based on the **thin-disk** (TD) technology which is particularly suitable for thermal management. In fact, this technology, quite complex to handle, has never been used in a French laser laboratory nor with new crystals such as Yb:CALGO. Despite a very strong international competition, the Lasers group, thanks to a recent collaboration with the **University of Stuttgart (IFSW)**, has succeeded in developing the **first passively mode-locked fs thin-disk Yb:CALGO oscillator** producing sub-200 fs pulses and 20 W average power (Fig. 2, [Ricaud OL 2012]). The future prospect of this activity is naturally to use the new architectures such as TD and single-crystal-fibre for higher power, high energy short pulse amplifiers (ANR Pampero).

Fibre based femtosecond laser sources:

The Lasers group performs research on high-power femtosecond laser sources based on rare earth-doped optical fibers, focusing its work on the generation of sub-100 fs pulses and on laser architectures that allow **energy scaling**. Starting from the **parabolic amplification regime**, we have studied a wide variety of nonlinear amplification architecture, and taken into account higher-order propagation effects such as the third-order dispersion and finite gain bandwidth to control the generation of high temporal quality, high-energy ultrashort pulses in ytterbium-doped fibre amplifiers, leading to **several record values for the couple pulsewidth / energy** (Hanna OE 2009, ANR HiPolyff).

This expertise in fs fibre systems has led us to collaborate with the LOA, Amplitude Systems, Imagine Eyes and the Hotel-Dieu hospital (ANR Greco) to work towards a **new laser tool for eye surgery** operating at the wavelength of 1610 nm, to reduce scattering effects in corneal tissues. The designed source is based on an ultrafast erbium-doped fibre amplifier, delivering energies of a few µJ [Morin OL 2009], sufficient to demonstrate the benefit of operating at this wavelength in ex vivo tests with pig and **human corneas**.

We also have been among the **first** teams in the world to demonstrate **coherent combining of several femtosecond lasers** (RTRA FemtoCombo, ANR CAN and MultiFemto), thereby providing a realistic way to scale arbitrarily the power emitted by such lasers. Various architectures have been studied and implemented in collaboration with Amplitude Systems, including **active** [Daniault OL 2011] and **passive beam combining** [Zaouter OL 2012], **multicore fibre** beam combining [Paurisse OL 2010], and **spatio-temporal coherent combining** [Daniault OE 2012], validating that coherent combining is possible for **pulses as short as 50 fs,** and obtaining pulse **peak power of 2 GW** from a fibre system. Large scale projects are now starting, based on this idea to build femtosecond lasers delivering Joules of pulse energy together with kW range average power, both in Europe (ICAN European project) and in the US.

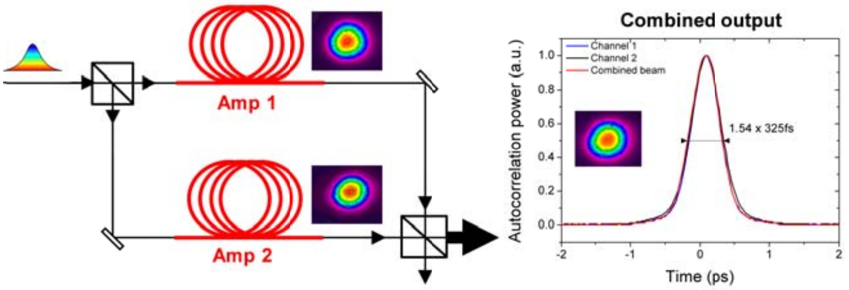


Fig. 3: first demonstration of coherent beam combining in fs regime

In the next years, we plan to build on this activity to explore different concepts related to coherent combining such as **pulse synthesis** (coherent combining of femtosecond pulses with different spectra, PALM PulseSynth), or **cavity enhancement** (coherent combining of successive pulses emitted by a mode-locked laser).

A.3 Development of the Front-end of the Apollon 10 PW laser facility

Initiated in 2007, the **Apollon 10PW project** (CPER Etat-IdF 2007-2013, Equipex CILEX), gathers several research laboratories of the Plateau de Saclay (LULI, LCF, LOA, CEA) with the purpose of developing a 10 PW (150 J in 15 fs) laser facility dedicated to laser-matter interactions. The Lasers group of the LCF is involved in this **large and very ambitious project** since the very beginning and has actively participated in the elaboration of its architecture. Moreover the Lasers group is in charge of the **front-end development** for this installation. The experimental implantation of the front-end started in October 2009 with a delivery time at the end of 2014. The front-end is one of the key elements of this project since it will provide the ultrashort pulses required to be able to reach the multiPW level. This front-end design was initially beyond the state of the art laser chain and includes an important research part. It is based on **Optical Parametric Chirped Pulse Amplification (OPCPA)** around two main axes of research: on **few-cycles pulse shaping and amplification** for the seed beam and **on a high-energy diode-pumped chain**

based on Yb-doped materials for the pump beam. This last point has a strong connection with our work on Yb:doped materials already established in the Lasers group (§2.2).

We have developed OPCPA stages using a high-energy diode-pumped chain and shown the advantage of such novel pumping scheme for high repetition rate (100 Hz) few-cycle pulses in the mJ range (Fig 4.).

Concerning the seed, much effort has been exerted to fulfill stringent requirements, especially in terms of bandwidth—supporting 10-fs pulses, and contrast—at least 10^{10}. We have focused our investigation on a powerful technique for this matter: **Cross Polarized Wave generation (XPW)**. By introducing a novel configuration mixing SPM and XPW in the same BaF$_2$ crystal, we have succeeded in obtaining several breakthroughs with the XPW technique in terms of duration: demonstrating 5-fs pulses as well as efficiency and reliability [Ramirez OE 2011]. This work has been successful thanks to the fruitful collaboration between the two lasers laboratories (LCF and **LOA**, RTRA NewXPW**)**, and the **CIMAP** which is specialised in fluoride crystal growth, and already our partner on Yb-doped fluoride crystals.

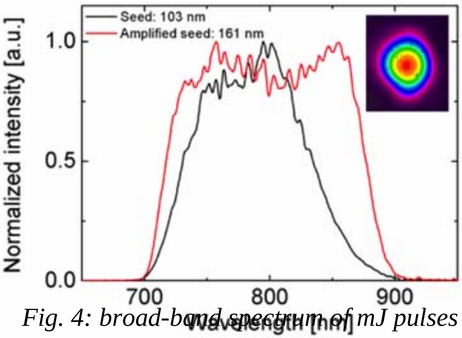


Fig. 4: broad-band spectrum of mJ pulses obtained in an OPCPA stage

A.4 Extended cavity semiconductor laser sources

Our work on semiconductor laser sources is focused on two topics, **optically-pumped semiconductor** lasers and **extended-cavity laser diodes**. Our aim is to take benefit of the very interesting properties of semiconductor materials (large spectral range, high efficiency, simplicity) in external cavities, which strongly control the laser oscillation qualities (spectrum and spatial).

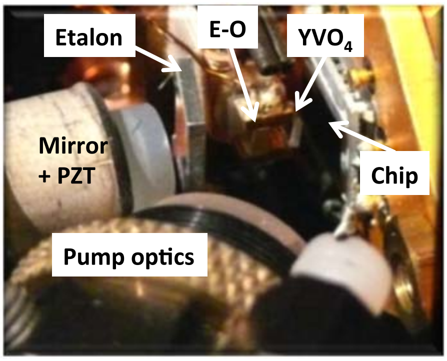


Fig. 5: close-view of the 2 frequency laser prototype

Optically-pumped semiconductors lasers (OPSL):

Dual-frequency oscillation of an OPSL is a new concept for the generation of a high-purity, optically-carried, microwave signal. Within a collaboration with LPN, TRT, LAC and SYRTE (ANR 2POLEVF, RTRA Lasomono), we have developed the very first dual-frequency OPSL emitting at 852 nm, with a tunable frequency difference, dedicated to the excitation of Cs atoms in a Coherent Population Trapping (CPT) atomic clock [Camargo PTL 2012]. A compact and robust laser prototype (Fig. 5) has been designed and characterized; the laser frequency was locked to the Cs D2 line at 852 nm, and the frequency difference between the two simultaneous laser lines was tuned around 9 GHz. A stable and high-purity RF beatnote was obtained for the first time, demonstrating the high coherence of the dual-frequency laser emission [Camargo SPIE 2013].

Our goal now is to use **this laser source to drive a Cs pulsed CPT spectroscopy setup**, which will result in an in-depth investigation of the laser noise properties and will validate this innovating laser architecture for high stability atomic clocks. In parallel we work with LPN on the improvement of the optical properties of the semiconductor active structures emitting at 852 nm, and on their thermal management, which is currently the major limitation to the laser output power (RTRA Power852).

Extended-cavity laser diodes array:

There is a strong interest to directly use high power laser diodes in material processing due to their high efficiency, compactness and reliability. However, their beam quality and related brightness are too low for most applications. Since many years, our work has been dedicated to the study of innovative designs to increase the beam quality of laser diodes arrays. Within a **European integrated project** (www.BRIGHTER.eu) involving 22 academic and industrial partners, we have demonstrated the **passive coherent beam combining** of an array of ten diode lasers at low power (1.7 W); the laser array was inserted in a spectrally-selective external cavity based on the **Talbot self-imaging** effect (Fig. 6), which favours the phase-locked operation of the lasers and forces a single laser line emission [Pabœuf APL 2008]. Simulations of the behaviour of the extended-cavity laser have been carried out with **University of Nottingham,** taking into account the free-space propagation in the external cavity and the propagation and amplification in the laser diodes through a 2D wide-angle finite difference beam propagation method coupled to a 1D isothermal electrical model of the lasers [Pabœuf JOSA B 2011].

We have also achieved **coherent combining** of infrared **Quantum Cascade Lasers** in collaboration with **Thales RT** [Bloom OL 2011].

Since 2012, we are involved in the FP7 European BRIDLE project[9] which aims at improving the spatial brightness of high-power direct diode laser systems at **2 kW cw power in 100 µm fibre** for thick sheets cutting. We will investigate different architectures of **passive and semi-passive coherent beam combining** with individually-addressable high-brightness laser arrays specifically developed for this application.

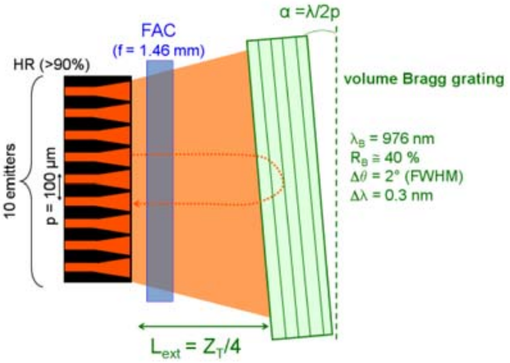


Fig. 6: passively phase locked laser array in a Talbot extended cavity

B. new starting projects

In addition to the projects and their continuation listed below, the Lasers group will start new projects:

B.1 LED pumped Solid state lasers

Pushed by the lighting market, the visible LED performance has dramatically improved in the past 5 years. In parallel, the cost in lumen per watt has been cut by one order of magnitude within the last two years. This represents a unique opportunity **to revisit the LED-pumping principle** which was abandoned in the early 1970s when efficient laser diodes appeared. As the pump represents the major cost of a diode-pumped laser source, LED pumping may lead to a breakthrough, with a considerable decrease of laser price. In addition, LED sources are extremely robust, operating in a large range of temperature and much less sensitive to electrostatic damage. A new family of industrial lasers may therefore arise between flashlamp-pumped and transversely-diode-pumped lasers. In the next years, we will investigate the visible LED pumping of solid-state lasers (ANR Edelveis, PALM TiSaLed, ASTRE pompage LED) including Nd doped crystals, solid state dyes or Ti:Sapphire within a **partnership with the company Effilux** and a **new PhD student** will start in October 2013.

B.2 Pressure phase matching for non-linear crystals

In order to open up a new degree of freedom for dispersion compensation in non-linear crystals, we plan to study the effect of **mechanical pressure** on a crystal, leading to refractive index changes by cw elasto-optic effect. To our best knowledge, this field of research has never been explored. It could lead to **new phase matching configurations** and new applications for existing and well-established crystals like KTP, LBO or BBO. In parallel with theoretical studies on pressure phase-matching, we will develop pressure-tuned cells for crystals and an experimental bench to test the potential of this new concept in a **partnership with the company Cristal Laser** (ANR NUTS).

B.3 Near infrared ultrafast few cycles sources based on OPCPA

Building on our Apollon 10PW front-end OPCPA, we are starting an activity in **mid-IR few-cycle Carrier-Envelope Phase (CEP) stabilized sources**. Indeed, it is widely established that long-wavelength ultrashort sources offer attractive characteristics for driving the high-harmonic generation processes in gases, including the **generation of attosecond pulses**. This research will benefit from our expertise in high power Yb-based laser sources since the pump laser is of utmost importance in parametric amplifier systems (CNRS Equipment, PALM MirOpcpa). We will also use our experience in coherent combining to carry out pulse synthesis experiments in this context. These aspects will be investigated in a **partnership with the company Fastlite**, which will fund a **PhD student from Octobre 2013**, and is interested in developing ultrafast systems in the mid-IR range. It will also be carried out in collaboration with the **Attophysics group from CEA Saclay,** a potential user for such sources.

2. Reputation and academic attractivity

The Laser group has been supported financially by a large number of projects during the 2008-2013 period in a local (4 RTRA "Triangle de la Physique", 3 Labex "PALM" and 1 ASTRE "Conseil Général de l'Essonne" projects), national (9 ANR "Non Thematique" and "Technologies de la Santé", 4 DGA projects) and international (3 FP7 European projects: BRIGHTER and BRIDLE and the ICAN feasibility study) calls. The group is member of two Equipex: CILEX through the Apollon 10 PW project and MORPHOSCOPE (from the LOB, Ecole Polytechnique).

Our scientific level is well recognized by the international community, as stated by the 96 articles published since 2008 in peer-reviewed journals and including 33 articles in Optics Letters, considered as the leading journal in

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[9] **BRIDLE** is coordinated by **Dilas Diodenlaser GmbH** (Germany); the consortium includes researchers from **University of Nottingham** (United Kingdom), the **Fraunhofer Institute for Laser Technology** ILT and the **Ferdinand Braun Institute** FBH (both Germany), the Laboratoire Charles Fabry (France) and the industrial partners **Modulight** (Finland) and **Bystronic** (Switzerland), www.bridle.eu.

our research field. P. Georges is ranked 1st in France and 18th in the world for the number of papers published in Optics Letters since 1983 (ISI Web).

Our group is also strongly involved in the academic research management. P. Georges has been member of the selection committees of the ANR "Non thématique" (Physics) and "ASTRID" (joint funding program between ANR and DGA French Army). P. Georges is member of the sub-committees "Extreme Light" from the RTRA "Triangle de la Physique" and "Ultrafast dynamic: from the sources to multiscale responses" from the Labex PALM (Physic: Atom Light Matter). Members of the Lasers group are active in two "CNRS networks on technological skills" from the CNRS (MRCT): "Femtosecond Technologies Network, RTF" (P. Georges until 2009 replaced then by F. Druon) and "Bulk crystals, Micro-nano-structures and Optical set-up, CMDO" (P. Georges until 2009 replaced then by F. Balembois). P. Georges is member of the Laser Advisory Committee for the XFEL-DESY in Germany and has reviewed the Conceptual Design Report for New Generation of free electron laser project (LUNEX 5) at SOLEIL. The permanent staff members are regular reviewers for the ANR, DGA and various funding agencies such as SNSF (Switzerland), Austria, Netherland... They are also regular reviewers for scientific journals such as OL, OE, JOSAB... and referees in many PhD thesis committees.

P. Georges has been General Chair of the "Europhoton Solid-State and Fiber Lasers 2008" conference and is now member of the Advisory Committee of this conference. P. Georges has been chair of the sub-committee "Solid State lasers" for the Cleo Europe 2011 conference, Program Chair of the CLEO Europe 2013 conference and will be General Chair in 2015. F. Druon has been member of the sub-committee "Solid State lasers" for the Cleo Europe 2011 and 2013 conferences and member of the scientific committee of the 2011 EOS Topical Meeting on Lasers.

F. Druon has been the recipient of the Jean Jerphagnon Prize in 2011 for our work on femtosecond fibre laser for corneal surgery, P. Blandin received an award for his thesis prepared in collaboration with the ISMO laboratory (Prix Perrissin-Pirasset en Sciences de la Chancellerie des Universités de Paris 2009), C. Gerhard received in 2009 the Georg-Simon-Ohm-Award from the German Physics Society for his "Diplomarbeit" performed in the Lasers group in 2006.

3. INTERACTION WITH THE SOCIAL, ECONOMIC AND CULTURAL ENVIRONMENT

All CNRS members of the Lasers group are teaching in various places (Master, IOGS, Supelec, ENSTA). Group members participate in dissemination through Open Days at the Institut d'Optique for the "Fête de La Science" and have been especially active for the celebration of the 50th anniversary of the laser in 2012 with a demonstration of laser marking experiment at IOGS and several conferences at Palaiseau, Lille and Lyon.

For many years, the Lasers group has developed strong links with many French companies. Since 2008, we had collaboration with: Amplitude Systemes, Cilas, Cristal Laser, Eolite Systems, Fibercryst, Horiba, Jobin-Yvon, Oxxius, Teem Photonics, Thales and we are starting new projects with Effilux and Fastlite. These collaborations allow us to have PhD student funded by CIFRE contracts involving industrials partner (7 PhD students since 2008) and research contracts. These partnerships are very fruitful since many former PhD students have positions in R&D departments of these companies and several products include our research results.

Specifically, we have a privileged collaboration with two companies: **Amplitude Systemes** and **Fibercryst**. For both of them, we have established a **common research laboratory**: one engineer is working full time with us, developing joint research projects with PhD students and sharing equipment provided by each partner. The PhD students are supervised by researchers from the Laser group and the research engineer from the company. This partnership is very efficient in terms of scientific publications, patents and new research projects and has an impact on the new products strategy of our industrials partners (Taranis module for Fibercryst and Tangerine fibre amplifier for Amplitude Systemes)

Since 2008 the Lasers group has filed six patents, and five of them were in collaboration with Amplitude Systems and Fibercryst, demonstrating the impact of these partnerships.

OPTICAL SYSTEMS AND COMPONENTS

SYSTÈMES ET COMPOSANTS OPTIQUES

(SCOP)

SCOP GROUP MEMBERS

Head: CHAVEL Pierre, Directeur de Recherche, CNRS

Equipe Systèmes d'Imagerie et Physique des Images (SPIm) / Imaging systems and physics of images

Head: GOUDAIL François, professeur IOGS/U. Paris-Sud

Permanent scientists :

BOFFETY Matthieu, maître de conférences IOGS/U. Paris-Sud (2012-)
KULCSÁR Caroline, professeur IOGS/U. Paris-Sud (2012-)
MEYZONNETTE Jean-Louis, professeur IOGS/U. Paris-Sud (2009-2012, retired 2012)
RAYNAUD Henri-François, maître de conférences U. Paris XIII, HdR (2012-)
SAUER Hervé, maître de conférences IOGS/U. Paris-Sud
TABOURY Jean, professeur IOGS/U. Paris-Sud (retired 2012)

Doctoral students

AYARI Noura	*graduated 2011*	*research engineer, SOFRADIR*
de la BARRIERE Florence ([10] with ONERA)*	*graduated 2011*	*research engineer, Thales Optronique*
BENIERE Arnaud	*graduated 2009*	*research engineer, MBDA*
BENOIT-PASANAU Céline	*graduated 2010*	*research engineer, ESSILOR*
DIAZ Frédéric (with Thales R&T)*	*graduated 2010*	*research engineer, Thales Angénieux*
DRUART Guillaume (with ONERA)*	*graduated 2008*	*research scientist, ONERA*
FERREC Yann	*graduated 2008*	*research scientist, ONERA*
GILLARD Frédéric (with ONERA)*	*graduated 2011*	*engineer in industry*
MINET Jean	*graduated 2011*	*post doc, USA*
MOULIN Gaid	*graduated 2009*	*engineer in industry*
PELOUX Marius	*graduated 2011*	*research engineer, ESSILOR*
ANNA Guillaume	2010- (polarimetric imaging)	
FRUGIER Pierre-Antoine (* with CEA)	2012- (image coding)	
GRULOIS Tatiana (* with ONERA)	2012- (miniaturized IR imagers)	
LU Shuxian (* with Renault)	2012- (imaging for driving assistance)	
MARTINEZ-HERRERA Sergio	2012- (polarisation in scattering media)	
SIVO Gaetano	2011- (adaptive optics)	

Visiting scientists and postdoctoral fellows

KUANG Dengfeng, Erasmus Mundus visiting scholar from Nankai University (2009)
NECHAK Lyes (2012-)
PIPONNIER Martin, post-doctoral fellow (2012-)
HU Haofeng, post-doctoral fellow (2011-), foundation franco-chinoise pour recherche scientifique et la technologie
FEZZANI Riad (2012-)

XUV Optics and Optical Surfaces

The reports of the XUV and Optical Surfaces teams have been merged into one and the same section.

Head, XUV Optics: DELMOTTE Franck, maître de conferences IOGS/U. Paris-Sud, HdR

Head, Optical Surfaces: MERCIER Raymond, maître de conférences hors classe IOGS/U. Paris-Sud

Permanent scientists :

BRIDOU Françoise, ingénieur de recherche au CNRS (retired 2011)
JOYEUX Denis, directeur de recherche au CNRS, (retired 2008)
MELTCHAKOV Evgueni, ingénieur de recherche à l'Institut d'Optique (2010-)
de ROSSI Sébastien, maître de conférences IOGS/U. Paris-Sud
RAVET Marie-Françoise, ingénieur de recherche hors classe au CNRS, (retired 2008)
VARNIERE Françoise, maître de conférences U. Paris-Sud (IUT)

Engineering support

The XUV and Optical Surfaces teams benefitted considerably from the engineering support staff, and in particular the opto-mechanical shop and Arnaud Jérôme, technology process engineer.

Doctoral students

BOURRASSIN-BOUCHET Charles	graduated 2011	post-doc, UK and France
HECQUET Christophe	graduated 2011	ingénieur de recherche au CNRS
EMPRIN Benoît (* with CEA)	2011-	

Postdoctoral fellows

MENESGUEN Yves (2008)	research engineer, CEA Saclay	CHOUEIKANI Fadi (2009-2011)	research engineer, SOLEIL.
ZIANI Ahmed (2009-2011)	postdoctoral fellow, CIMAP Caen.	MAURY Hélène (2007-2009, CEA/LCF)	engineer R&D, Essilor

Master level students: 14 students were hosted on short internships for a total of 37 months

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[10] (a star * indicates a graduate student advised by a permanent member of the group but not hosted in the group on a regular basis)

1. SCIENTIFIC REPORT

The “Optical Systems and Components” group, created in 2005, has brought together activities of Laboratoire Charles Fabry principally devoted to designing and demonstrating new imaging instruments, the associated components, and the associated signal processing techniques, including design, fabrication, testing, and applications. In many cases, imaging is extended to spectroscopy. While rooted on physics, materials science, and signal processing research that lends itself to publication, the group’s activity is also conducted in close collaboration with partners from the academia, other research institutions, and industrial research activities.

The activities of the former “XUV Optics” and “Optical Surfaces” teams, both located in the Orsay building, were essentially merged, while the SPIM team activity, in Palaiseau, was conducted separately. That situation reflects in the present report, where we have highlighted the results that we consider to be of world class, as also demonstrated by our publications, rather than seeking exhaustiveness. However, while the SPIM team has maintained a satisfactory rate of recruitment, experience has repeatedly shown over the years that it is difficult to attract scientists in the domain of XUV and Optical Surfaces, both as doctoral students and as permanent staff members; a specific solution must be found for this activity to meet its bright perspectives at hand (including in terms of project funding). It should be stressed that the XUV / Optical Surfaces activity receives considerable and regular contributions from the technical support engineers and technicians (optical workshop, mechanical design, clean room technologies).

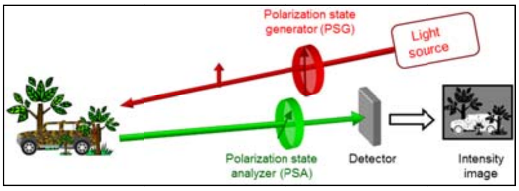
A - Imaging Systems and Physics of Images (SPIM)

The research topic of SPIM is the design of innovative imaging systems that take into account physical phenomena, optical engineering, and digital processing algorithms. Indeed, besides the optics, imaging systems involve signal processing algorithms that extract information from the initial image. Therefore, to optimize information extraction, it is necessary to take into account the physics of the observed scene and the noise sources. Considering all these aspects from the very beginning of the design process gives way to new powerful methods for imaging systems.

We use that global approach to address our two main research subjects: polarimetric imaging and the co-design of optical systems and information processing algorithms. Because of the applied nature of our research, the strategy of SPIM is to build long-term partnerships on those two subjects both in the industrial and public sectors. In addition, we give advice to industry on challenging application-driven topics.

A1. Polarimetric imaging

Active polarimetric imagers illuminate the scene with light of a given state of polarization and analyse the polarization of the light scattered by the scene (Fig. 1). They can reveal contrasts that do not otherwise and have demonstrated their efficiency in remote sensing, biomedical imaging, and industrial control. We have shown theoretically that a significant contrast increase between an object of interest and the background of the scene can be obtained by dynamically optimizing the illumination and analysis polarization states[11], and we have built an imaging system where these states are electronically controlled by liquid-crystal cells [12]. This is the first demonstration of a fully adaptive polarimetric imager. In Fig. 2, it is used to reveal objects behind diffusive media[13] (Fig. 2).



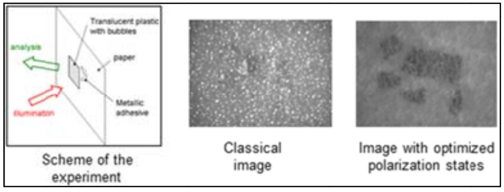


Fig. 1   *Fig. 2*

This work was performed in close collaboration with Thales Research and Technology, through the PhD theses of Arnaud Bénière (2006-2009, Thales PhD Prize 2010), and Guillaume Anna (2010-2013), andthrough international collaborations with University of Arizona[14] and Universtiy of Chernivtsi, Ukraine. It is funded by DGA through the ASTRID project Autopol (collaboration: Thales R&T and Institut Fresnel, Marseille), with the aim to fully automatize contrast optimization of a real time adaptive polarimetric imager through image segmentation[15]. We plan to explore other application domains, e.g. navigation using polarization cues in the sky (industrial partnership) and polarization-resolved endoscopy (partnership with physicians of the hospital of Boulogne).

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[11] F. Goudail, A. Bénière, ”Optimization of the contrast in polarimetric scalar images”, Opt. Lett., 34(9), 1471 (2009).

[12] G. Anna et al., “Fully tunable active polarization imager for contrast enhancement and partial polarimetry”, Appl. Opt., 51, 5302 (2012).

[13] G. Anna et al., “Polarimetric target detection in the presence of spatially fluctuating Mueller matrices”, Opt. Lett., 36, 4590 (2011).

[14] F. Goudail, J. S. Tyo,“When is polarimetric imaging preferable to intensity imaging for target detection?”, J.Opt. Soc. Am. A 28, 46 (2011).

[15] G. Anna et al., “Joint contrast optimization and object segmentation in active polarimetric images”, Opt. Lett. 37, 3321 (2012).

A2. Co-design of imaging systems

Co-design consists in designing an imaging system by taking into account from the beginning both the optics and the processing algorithms. This global approach can lead to performance enhancement, e.g., increase of the depth of field, decrease of size, weight and/or cost. This is possible thanks to the combination of progress in optical technologies, that make it possible to reliably fabricate tiny modulating structures, and to the fact that more and more computation power is available within imaging systems. This topic is quite hot in optical engineering, and SPIM is in very favourable context to address it, because of the expertise available at the IOGS in the domain of optical design and a rich local academic and industrial context in the domain of optronics and image processing.

A.2.1 Increase of depth of field by wavefront coding

There is often a need to increase depth of field or depth of focus of imaging systems. This can be done by inserting proper pupil phase masks. However, these masks tend to degrade the raw image quality, and digital deconvolution algorithms are needed to restore images. Optimizing the deconvolved image under appropriate quality measures, we ended up with phase functions that deviate from those proposed in the literature. Based on these results, a demonstrator was built during the PhD thesis of Frédéric Diaz (funded by Thales R&T) with a commercial long wavelength infrared camera, a custom made phase mask and a video-real-time digital deconvolution algorithm[16]. A three-fold depth of field increase has been obtained, leading to record image quality (Fig. 3). This project will be continued with the same partner, the goal being to optimize not only the phase mask but also the whole optical combination around it, by using such modern optical design software as CodeV.

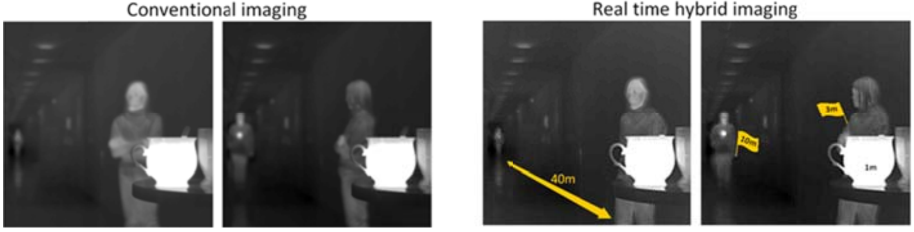

Fig. 3: Demonstrator of infrared imager with enhanced depth of field

A.2.2 Miniaturized Infrared imaging

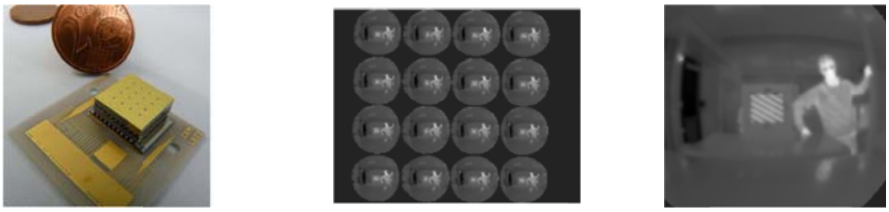

Fig. 4: On chip 16 channel infrared camera, acquired series of 16 images, reconstructed image.

Miniaturizing optical systems is a research area of current interest for civil and defence purposes. We have worked with ONERA at designing very compact optical systems for cryogenic infrared imagery applications, which could be integrated near the cooled detector and ideally directly on it. Since that cannot be done with standard optics, we have used a biomimetic approach, drawing inspiration from insect eyes. This topic was developed during the PhD theses of Guillaume Druart (2006-2009, EADS Foundation PhD award 2010, ParisTech PhD award 2010 and Florence de la Barrière (2009-2012, ONERA PhD Prize 2012)[17] (Fig. 4).

A3. Evolution and growth of the team

In September 2012, Pr. Jean Taboury, leader of the team, retired. The same year, a new associate professor, Matthieu Boffety, joint the team to work on polarimetric imaging and develop the application to life science and imaging through scattering media. Furthermore, an experienced researcher, Caroline Kulcsár, was recruited as a professor at IOGS, and joined the SPIM team together with a colleague (Ass. Pr.) Henri-François Raynaud. Both are specialists of modelling and control in adaptive optics, with applications to astronomy (on-sky tests within the CANARY project – lead by Univ. of Durham – at the William Herschel Telescope in La Palma) and to retinal imaging (ANR project ReVeal lead by Institut de la Vision). While thereby extending the range of applications addressed by SPIM, which will now include adaptive optics, their skills also encompass superresolution and registration algorithms for digital video sequences, which reinforces the team capacity in polarimetric imaging and codesign algorithms.

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[16] F. Diaz et al., “Real-time increase in depth of field of an uncooled thermal camera using several phase-mask …”, Opt. Lett. 36, 418 (2011).

[17] De La Barrière et al., “Compact infrared cryogenic wafer-level camera: design and experimental validation”, Applied Optics 51, 1049 (2012).

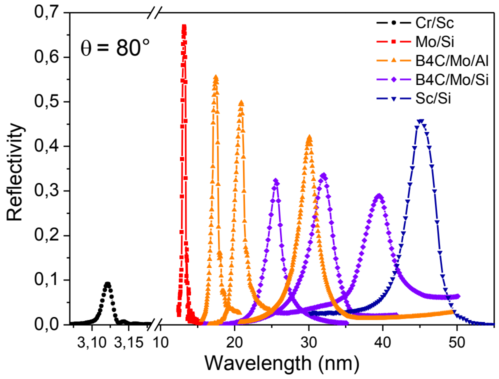
B - XUV Optics and Optical Surfaces

Multilayer optics with high surface precision are key components for several scientific and industrial fields in the soft X-rays (0.1 nm to 10 nm) and Extreme UV (10 nm to 100nm) spectral ranges: EUV lithography, astrophysics, high field physics, ultrafast physics, dense plasmas, ... Rapid progress in those applications induces new requirements on multilayer optics: higher reflectivity, but also more generally a better control of the spectral response (narrowband or broadband mirrors, enhanced spectral purity, phase control, …). Our research activities focus on three main axes which are described in the first three subsections: EUV Imaging of the solar corona, optics for attosecond pulses and dense plasma diagnostics. Other significant activities are summarized in the last subsection.

We will actively pursue these activities in the future, including in particular the development of attosecond optics in the ATTOLAB project (Equipment of Excellence program with CEA). Likewise, our expertise in optical components and optical surfaces will be crucial for the MORPHOSCOPE project (Equipment of Excellence program with LOB) where we must develop an X-ray microscope for cell imaging with nanometer resolution.

B1. EUV Imaging for Astrophysics (Solar Orbiter Mission)

Laboratoire Charles Fabry has been involved for a long time in the study and development of EUV telescopes for the observation of the solar corona, in collaboration with Institut d'Astrophysique Spatiale, Orsay. The SoHO and STEREO missions have been producing solar images from satellites with our mirrors for many years. We are supported by the French Space Agency (CNES) to participate in the European consortium on the EUV imagers for the Solar Orbiter mission of the European Space Agency. Our contribution is the realisation of the mirrors for two telescopes, a single-mirror telescope that will give a full image of the Sun (FSI, Full Sun Imager) and a two-mirror telescope giving a detailed image of a portion of the Sun (HRI, High Resolution Imager).



Reflectivity spectra of mutilayer mirrors measured on synchrotron radiation source near normal incidence (Elettra, BEAR beamline)

Our main activity in the Optical Surfaces team has been devoted to the fabrication of the substrates to be multilayered by the XUV Optics team. This has included the design of the substrates in order to maximize the chances of meeting the demanding specifications of the astrophysicists. The substrates were fabricated by our optical workshop and we did the required metrology. The technique is to start off with the classical polishing techniques in order to achieve a spherical surface with a high precision in shape and a very low roughness (less than 0.2 nm RMS is required, due to the very short wavelengths to be reflected), and then to transform this spherical surface into a hyperbola, while preserving the roughness. This is achieved by broad ion beam etching, a technique developed by our team in an axi-symmetrical version and applied in the past to several NASA missions (GALEX and STEREO). We have extended this technique to off-axis mirrors, such as those required for Solar Orbiter. Having solved all the problems, we have now finished the three substrates of the FSI mirrors, including the associated metrology intended to ease the task of the IAS for the integration of the mirror in the instrument. The next step will be the HRI mirrors, where the specs are much more stringent (2nm RMS shape defects).

Concerning EUV multilayer coatings, we have proposed the concept of dual-band mirrors. Such coatings made by stacking 2 periodic multilayers spaced by a thin layer reflect efficiently two spectral lines with enhanced spectral selectivity.[18] This function has been optimized with respect to the multilayer parameters and coating materials. It is currently being be implemented on the Solar Orbiter Full Sun Imager. We have investigated the use of Al instead of Si in periodic multilayers for increased efficiency. The actual challenge here is the large roughness due to the Al

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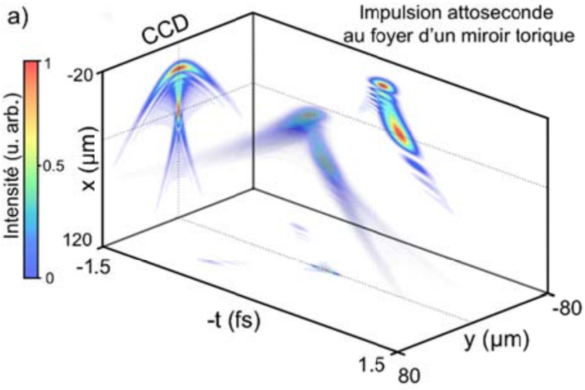
[18] C. Hecquet et al., "Design and performance of two-channel EUV multilayer mirrors …", Appl. Phys. A95, 401 (2009)

layers polycrystalline structure, which induces a significant loss of reflectivity. By optimizing the deposition process and by adding a third material (B_4C) in the periodic stack, we have been able to smooth the interfaces down to 0.5 nm. Thus, reflectivity higher than 50% at 17 nm has been measured on synchrotron beam lines with SiC/Mo/Al and B_4C/Mo/Al structures, see figure. This is the highest reflectivity ever reported for such wavelength.[19]

B2. Attosecond Optics

The production of attosecond pulses in the extreme ultra-violet domain (XUV) has been made possible through high-order harmonic generation. The availability of such pulses has impacted a variety of domains such as chemistry, surface science, molecular and atomic physics. Since 2005, our team has been involved in the development of multilayer mirrors to transport attosecond pulses and at the same time compress them down to their Fourier transform by controlling the optical phase over a broad XUV spectrum, from tens to hundreds of electron-volts. In collaboration with CEA-Saclay, we have experimentally demonstrated the first compression of attosecond pulses with multilayer mirrors. These metrological tools have enabled us to develop a sub-50as compression scheme based on the combination of a metallic filter and a multilayer mirror.[20] XUV attosecond pulses are usually characterized with spectrally resolved correlation techniques, such as RABBIT or FROG-CRAB. Those involve focussing the pulses into a spectrometer with either a grazing incidence toroidal mirror, or a near normal incidence spherical mirror. However, geometrical aberrations resulting from the latter mirrors induce spatio-temporal distortions (figure) which are often underestimated. We have introduced numerical[21] and analytic[22] tools to quantify such distortions.



Spatio-temporal profile of an attosecond pulse reflected off a toroidal mirror, and its x-y and x-t projections.

This work has been supported by the National Research Agency (ANR) and the RTRA Triangle de la Physique. Future developments will be supported by the Equipment of Excellence Attolab funded by the ANR program "Investments for Future 2011". The project brings together nine partner laboratories from seven research institutions.

B3. Advanced X-ray diagnostics for dense plasmas

X-ray imaging systems and X-ray spectrometers are key diagnostics for Inertial Confinement Fusion (ICF) experiments. In close collaboration with CEA, we are developing advanced X-ray diagnostics to probe dense plasmas produced in the future Laser MegaJoule (LMJ) facility.

For imaging diagnostics, we have developed non-periodic W/SiC multilayer mirrors specifically designed to reflect photons on a broad spectral range: from 5 keV up to 10 keV. The mirrors were optimized with a homemade calculation code and provide high reflectivity (> 35% at 0.7° grazing incidence) in almost the full energy range. A specific methodology has been developed to accurately determine the coating parameters (layer thickness, roughness and index). Reflectance measurements at the PTB synchrotron facility (BESSY II, Berlin) show good agreement with models over the whole range.[23] The CEA has chosen to implement this coating on several LMJ imaging diagnostics.

Concerning broadband spectrometry of dense plasmas, there is a specific need to develop multilayer optics with a specified (non flat) spectral response and a good rejection of unwanted bands (at both higher and lower energies). We have designed non-periodic Cr/Sc multilayer mirrors in order to reflect photons in the energy range 2-4 keV with a pre-defined reflectivity profile. Numerous combinations of layers have been investigated with two or three different materials in the multilayer. Interface effects that may induce effective thickness changes has been investigated and were taken into account when controlling layer thicknesses (from sub-nanometer to several nanometers). The final

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[19] Meltchakov et al., "Development of Al based multilayer optics for EUV", Appl. Phys. A98, 111 (2010).

[20] C. Bourassin-Bouchet et al., "Shaping of single-cycle sub-50-attosecond pulses with multilayer mirrors", New J. Phys. 14 (2012)

[21] C. Bourassin-Bouchet et al., "Spatiotemporal distortions of attosecond pulses", J. Opt. Soc. Am. A27, 1395 (2010)

[22] C. Bourassin-Bouchet et al., "Duration of ultrashort pulses in the presence of spatio-temporal coupling", Opt. Exp. 19, 17357 (2011)

[23] H. Maury et al., "Design and fabrication of supermirrors for 2-10 keV X-ray plasmas diagnostics", Nucl. Instr. and Meth. A 621, 242 (2010)

results obtained with a 100-layer non-periodic coating show good agreement with the requested reflectivity profile.[24] This study opens the way towards apodization and more generally spectral shaping in the soft X-ray domain.

2. Reputation and academic attractivity

The SCOp group has been supported financially through seven ANR projects submitted in response to national calls, two European projects (FP6 and FP7), and one project from Conseil général de l'Essonne. It participates in two EQUIPEX projects for innovative XUV instruments. The national agencies CNES and CEA have supported most of the XUV projects. During the reporting period, the total annual financial support to submitted projects from the group averages to slightly over 300000 euros per year, with approximately 70% to the XUV and surfaces teams, which heavily rely on expensive technology, and 30% for the SPIM team. As mentioned in the preceding section, three doctoral students of the group were recognized by doctoral prizes. P. Chavel has been a member of the scientific Council of CNRS, 2005-2010, and of the science and technology committee of ONERA, 2002-2011. He has served on the Scientific Committee of the Max Planck Institute of the Science of Light since the creation of that Institute in 2009. F. Delmotte is currently the chair of the OSA Technical Group on **Gamma, X-Ray and Extreme UV Optics. F. Goudail is a topical Editor for Applied Optics and has organized national workshops on Nonconventional Imaging with the support of GdR Ondes, GdR Images and the French Optical Society every year since 2005.**

Two further activities of the XUV team deserve mentioning at this stage.

Compact, tunable XUV source

The team participates in the development of a new tuneable compact XUV source for spectroscopic use. Photons are emitted by a parametric radiation of electrons through a periodic multilayer structure. Our role is to produce the multilayer targets deposited on very thin membranes (~100 nm thick). A specific development of laterally graded multilayer targets is under way. The development of the source is under the responsibility of Laboratoire de Chimie, Physique, Matière et Rayonnement and is funded by ANR project TPLUS.

The CEMOX platform

The XUV team is a major partner of CEMOX (Centrale d'Elaboration et de Métrologie d'Optique X), a facility operated as a platform of Federation de Recherche LUMAT. CEMOX consists of a four target magnetron sputtering machine and an EUV plasma laser reflectometer and has been complemented in 2010 with a new X-ray reflectometer through the support of Conseil Général de l'Essonne (ASTRE project in collaboration with SAGEM-REOSC). Numerous multilayer coatings have been deposited and characterized for the XUV scientific community: selective or broadband mirrors for HHG experiments (LOA, ISMO, CEA Saclay), mirrors for X-ray laser experiments (ISMO, LaseriX), synchrotron optics (SOLEIL). CEMOX is also open to specific industrial requests: we have produced multilayer coatings on synchrotron radiation optics for Mecaconcept and thin film coatings for Winlight.

3. INTERACTION WITH THE SOCIAL, ECONOMIC AND CULTURAL ENVIRONMENT

Diffusion of research expertise to industry is one of the historical missions of the IOGS. SCOp has been very active in this domain, using its skills in spectral imaging, diffractive optical elements design, and XUV Optics to address challenging industrial projects. On all our projects, innovation is our priority, leading to publications and/or patents. In fact, as mentioned in the "Scientific Production" section, most of the group's research activities involve some industrial partner (Thales, Sagem) or some non-academic research institution (ONERA, CEA, CNES), so that the distinction is sometimes artificial. Collaboration with ONERA has been organized for ten years under the bilateral collaborative research agreement PRECISION. Some additional projects where the partner's need was the main driving force are mentioned below.

Micro-optics

SCOp has been a partner of the NEMO (Network of Excellence in Micro-Optics) and ACTMOST () projects funded by the EU Framework Programmes 6 and 7. Most of the activity there was devoted to initiating collaborative research with European industrial partners. In both cases, Pierre Chavel was a member of the project executive board and the coordinator of modelling activities.

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[24] F. Bridou et al., "Design and fabrication of X-ray non-periodic multilayer mirrors …", Nucl. Instrum. and Meth. Section A 680 (2012)

Spectral imaging (SPIM)

Spectral imaging is the acquisition of the image of a scene in a large number of spectral bands. SPIM has developed in the past years a high étendue imaging static Fourier-transform spectrometer in the visible range named CaHyd. To respond to an industrial demand of Thales Optronique, we designed and built a demonstrator in the infrared domain (3µm-5µm) named *DéSI²R* and investigated its performance during the PhD of Noura Matallah[25]. Our expertise on spectral imaging systems has also been put to use in collaboration with Sagem (PhD of Jean Minet) on a multispectral imager acquiring several spectral channels in parallel. The goal of this project, tightly linked to information extraction from spectral images, was to determine the optimal set of spectral channels useful for a given target detection task[26].

Design of pixelated optics (SPIM)

The SPIM team has also applied its expertise on optical diffractive elements to the design of pixelated phase masks. Such masks are attractive because the phase of each pixel can be controlled independently, but spatial sampling and phase quantification create image defects. We collaborated with Essilor, which develops these technologies for ophthalmic applications and supported two doctoral theses. As an example, we introduced a pseudo-random spatial sampling strategy which minimizes these defects in the context of human vision[27]. Some ideas have been patented[28].

Coatings for Vacuum Ultra-Violet (XUV)

Following previous work on thin film mirrors and polarizers for the VUV spectral domain, we have investigated the physicochemical and optical properties of ion beam sputtered aluminium thin films with magnesium fluoride protective layers. This CNES supported study aims at introducing new functions for Ly-α instruments (λ=121 nm).

Alternate multilayer gratings (XUV)

In collaboration with synchrotron SOLEIL and Horiba Jobin-Yvon (project RTRA Triangle de la Physique), we have fabricated a multilayer grating which has a very high efficiency in the photon energy range from 1000 to 2500 eV, by coating a lamellar grating of 2.5 nm groove depth with a periodic multilayer. We have designed and fabricated a 2D periodic Mo_2C/B_4C structure which, when deposited on a grating with a groove depth equal to the layer thickness, provides a nearly perfect blaze effect in the specified grating diffraction order.[29] A peak diffraction efficiency of nearly 27 % was measured at 2200 eV, in good agreement with numerical simulations. This grating will be used in the Deimos beamline at SOLEIL together with a matched multilayer mirror that we have designed and fabricated as well. Similar systems will be developed for other beam lines in the future.

Finally, concerning scientific culture, the group has been involved essentially every year in the “Journées de la Science” on the Paris-Saclay campus, including inside our building. Sébastien de Rossi has played a coordinating role. For two years (2010-2012), Pierre Chavel has initiated and organized a series of lectures on the general theme of lasers for the benefit of high school students from the neighbourhood on the occasion of the fiftieth anniversary of the laser. He is also the current president of the French Physics Olympiads (high school level).

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[25] Y. Ferrec et al., “Noise sources in Imaging Static Fourier Transform Spectrometers”, Optical Engineering, 51, 111716 (2012).

[26] J. Minet et al. “Influence of band selection and target estimation error on the performance …”, Appl. Opt. 50, 4276 (2011).

[27] C. Benoît-Pasanau et al., "Reducing the diffraction artefacts while implementing a phase function on an SLM" Appl. Opt. 50, 509 (2011).

[28] J. Ballet et al. "Réalisation d'un composant optique transparent à structure cellulaire", patent filed May 20th 2010, FR1053977.

[29] F. Choueikani, “X-ray properties and interface study of B4C/Mo and B4C/Mo2C periodic multilayers”, Applied Physics A (2013)

3. Interaction with graduate education

The Laboratoire Charles Fabry (LCF) has a unique situation: it is a laboratory devoted to optics in an institute devoted to optics. While optics has been the theme of the institute for almost a century now, it is remarkable to realize that more than 50% of the current research topics were non existing thirty years ago: quantum optics was in its infancy while nanophotonics, atom optics or optical coherence tomography were not even dreams. They are now at the center of the institute research and training programs. This simple remark is a good introduction to the strategy of Institut d'Optique (IOGS), which is based on three ideas: focussing on optics, introducing new topics to cover modern aspects of optics, maintaining the interaction between research, training, and innovation.

Since it was founded, it has been a tradition of IOGS to be at the forefront of the discipline both in research and in teaching. The Institute professors are committed to serve the industrial and academic community by continuously developing new research topics and new training courses. In order to achieve these goals, it is necessary to take advantage of all human resources. It is thus no surprise to realize that virtually all the scientists holding a permanent research position are involved in both research and teaching. In what follows, we describe more specifically how the faculty members of the LCF share their expertise in the training programs of the Institute of Optics and of the neighbouring institutions such as Université Paris Sud, Ecole Polytechnique, and Ecole Normale Supérieure de Cachan, to name a few.

Master programs

Faculty members from Charles Fabry are involved in five different master programs:

- the engineering degree of Institut d'Optique – Graduate School, which by European "Bologna" standards is a master degree in optical engineering
- the engineering degree of Ecole Polytechnique (4 researchers are professors at Ecole Polytechnique)
- the Physics for Optics and Nanoscience (PON) international master program, taught in English (jointly operated by IOGS, Ecole Polytechnique, ENS Cachan and Université Paris Sud),
- the Optique, Matière Plasma (OMP) master program jointly operated by IOGS, Université Paris-Sud, Ecole Polytechnique, UVSQ, UPMC (Paris 6).
- the Nanosciences master program jointly operated by by IOGS, Université Paris-Sud, Ecole Polytechnique, UVSQ, Supelec, Ecole Centrale Paris, ENS Cachan.

Virtually all members of LCF are involved in the engineering degree program with over 100 students per year. All those in charge of this program (JM Jonathan, F Goudail, F. Marquier, G Messin and D Boiron) belong to the LCF. The PON program is operated by Ecole Polytechnique. Four professors from LCF are involved. The head of the Optics track of the Optique, Matière, Plasmas (OMP) program is N Dubreuil and the head of the Nanophysics track of the NanoScience Master is JJ Greffet, both from LCF.

A key feature of the training at IOGS is the importance of the experimental training. The training lab can host 100 students simultaneously with state of the art equipment. LCF contribution is essential as 85 % of the lab classes are taught by LCF members. It is worth mentioning that faculty members of LCF introduce new lab classes on a regular basis. Hence, the novelty goes from the lab to the students in a very efficient way. In the last period, we have introduced new lab classes for our master students on the i) Hong, Ou, Mandel experiment of quantum optics, ii) optical tweezers and iii) a spatial light modulator. The test of the violation of Bell inequalites had been introduced ten years ago.

From the lecture point of view, the update of the courses is a smooth continuous process. Our policy to make sure that courses are regularly updated is to simply take advantage of the fact that there are specialists of all the topics in the Paris area. Hence advanced master courses at the M2 level are taught by the best experts of the field. They naturally include new material in the courses as the state of the art changes. When new topics emerge, they are first introduced as optional courses in the curriculum. They may become common core courses later on. The contribution of the LCF faculty to this process is essential: All the groups of LCF have members giving lectures at the M2 level.

An important contribution of the LCF to the students training is by hosting internships. The lab hosts on average 50 M1 or M2 students for a period ranging between 2 and 5 months.

PhD program

The LCF is strongly involved in the doctoral training program. 80 students graduated in the period 2008-2013. The current number of PhD students is 46 for a total number of 27 faculty members with an habilitation. Hence, the faculty members of the lab manage to be close to the upper limit. It is worth mentioning that each advisor can supervise a maximum of three PhD students in order to ensure a close collaboration. This close supervision and a selective recruiting process ensures that the PhDs can be completed in 38 months on average with a relatively low rate of unfinished PhDs of 6%.

The lab organizes a nearly weekly seminar. Each student gives a talk during its PhD preparation and doctoral students are expected to attend the talks. The head of the lab has an interview with each student every year. All the students working at LCF have a grant. The typical doctoral contract corresponds to 1685 euros per month. The minimum accepted income corresponds to China Scientific Council grants of 1200 euros net per month.

Given that all the groups of LCF are working with PhD students, we do not repeat the scientific production analysis here.

While essentially all course work has been taken before the end of the master degree, all the students are requested to take only two scientific courses of 25-30 hours and one training period focussed on professional skills (so-called doctoriales) of 35-40 hours during the PhD. PhD students have also the opportunity to be teaching assistants (monitorats). We have 24 graduate students teaching every year. The typical monitorat contract corresponds to a duty of 64 hours per year with an extra salary of 280 euros net per month.

An important issue is the professional career of our alumni. The LCF has an active policy to make sure that we follow their career. When looking at the five last generations, we observe that a fraction of 66 % of our doctors has a permanent position while 22% are doing a post doc and 2% looking for a job. Among the 80 students who graduated, 50% have a permanent position in private companies and 20% an academic permanent position. Our doctors are mostly working in France (70%), the rest being either in the rest of Europe (17%) or outside Europe (13%).

Of those 80 graduates, 2 defended their doctorate before the prescribed term of 36 months and 47 between 36 and 40 months. 20 needed an additional few months and defended before 44 months. The other 10 needed more time either because of employment duties (e.g., being an assistant professor in a foreign university) or because of experimental difficulties. The average is 40.4 months.

The LCF is strongly involved in the doctoral school "Ondes et Matière" (“Waves and Matter") co-operated by Université Paris-Sud and Institut d'Optique Graduate School. Pierre Chavel, now head of the LCF, has been deputy director for the last five years. The new head of the doctoral school is Jean-Jacques Greffet, from the Naphel group of LCF. The “SPIm” team as well as Michael Canva, Arnaud Dubois and Julien Moreau of the Biophotonics group are members of the STITS doctoral school (Sciences et Technologies de l’Information, des Télécommunications et des Systèmes).

International networks

The optics master program is a member of the Erasmus Mundus program OpSciTech operated with Imperial College in London, Friedrich Schiller University in Jena, Delft University of technology and Warsaw University of Technology. With this program, we have hosted 8 or 9 foreign students during one semester on average every year since 2007 while 4 or 5 IOGS students went abroad on the OpSciTech program. 4 or 5 OpSciTech students did their internship in the LCF every year.

LCF is a member of two Marie Curie Initial Training Network (ITN) programs: the “COHERENCE” network involves 18 research institutes and industrial partners located in 9 European countries and the USA. COHERENCE focusses on the creation and manipulation of Rydberg atoms and their applications to science and technology. The “ADOPSYS” network, with 8 academic members and 2 industrial members, all from Europe, is devoted to advanced optical systems design (global optimisation, inverse problems in imaging, co-design).

The Entrepreneurship program FIE and the LCF.

FIE (Filière Innovation Entrepreneurs) is an entrepreneurship track for the students at IOGS. This curriculum concerns mainly the engineer students over the three years of the engineer program (the "size" of the program is typically 100 hours in first year, 200 hours in second year and 250 hours in third year, with 20 students each year). FIE provides real world, hands-on learning on what it’s like to successfully transfer knowledge into products and processes that benefit society in the field of photonics. FIE is a generator of new opportunities of business activities detected in research labs or companies that are connected with Institut d'Optique. Launched in 2006, the FIE program has scanned and explored the potential of more than 80 different ideas related with photonics. So far, it led to the creation of 11 start-ups generating a turnover of more than 4 millions € in 2012. FIE students and companies have earn more than 40 prizes recognizing the quality of the innovation in the projects.

LCF plays a major role in the FIE: since 2006, LCF researchers have proposed 7 ideas to FIE program. LCF also provides scientific support to many other FIE projects by advising students and bringing the opportunity to use costly devices for characterisations (interferometry measurements, temperature mapping by thermal imaging to name a few). Moreover, the main initiator of the FIE program (François BALEMBOIS) is a professor in the Lasers group of the LCF.

4. Strategy and perspectives for the next contracting period

Laboratoire Charles Fabry sees itself as an active research unit involved at the appropriate level, i.e. at par with international counterparts, in research on various fields of Optics and Photonics. Looking at the publication record and the various signs of recognition of its contributions, it feels that it enjoys a good reputation. Because of its size, it cannot cover all of Optics and Photonics, but is instead organized in groups that sample a fraction of that domain. The size of the groups is in general appropriate to make noteworthy contributions to their specific domain. For that reason, strategy is to a large extent elaborated inside the group: each of the eight groups has briefly described its vision of its future activities in the next few pages. The main role of LCF is therefore to provide support to its group for implementing their strategy by allocating new positions, space and other facilities in the most efficient possible way. But that is not sufficient.

Indeed, it is essential for the LCF as a whole to have a strategy. The purpose of such a strategy is to encourage a common vision of the future of the field of optics, identify the opportunities for cross-fertilisation between groups, and detect emerging domains where establishing new groups would be a smart move. Looking back, in the recent past, that is how LCF has been able to take new initiatives. The Nanophotonics and Electromagnetism groups has emerged (in several steps since 2002) from the identification of common interest by several groups of that time in nanostructures, and by the strategic decision to be present on the emerging scene of nanophotonics and the associated nanotechnology. In 2011, the Biophotonics group was created after interaction among the various scientists in the groups who shared an interest in developing original optical instrumentation of biological and medical interest in partnership with medical doctors. There is now a need for thinking about the next stages, perhaps in relation with current worldwide reflections about the increased role of optics in information technology and for energy applications – LCF already has activities along those lines, it will need to think about new ambitious initiatives.

To contribute to its strategy, LCF is essentially well positioned nationally and worldwide by its network of academic and industrial collaboration. Tracks for further progress are identified. The Paris-Saclay territory is a particularly active area of development for new initiatives, or at least for a new structure of research partnership locally; LCF is present through its involvement in several Labex and Equipex. Its relation to the Saint-Etienne and Bordeaux sites of IOGS, both associated with CNRS for their research activities, is an opportunity for spanning a broader fraction of the Optics and Photonics realm: dialog with the Saint-Etienne and Bordeaux laboratories will be organised on a regular basis. LCF is also present in the international optical community through conferences and learned society activities. It follows the activities of the Photonics 21 European platform and the French Optics clusters. IOGS as a whole participates in the "outreach" initiative ECOP (European Centres for Outreach in Photonics), which is organized in a consortium and has received support from the European Framework Programme (GoPhoton, FP7). A stronger involvement in those initiatives could be appropriate.

Atom Optics: perspectives

The main intellectual thrust of the group, the use of **ultracold atoms to explore many-body physics**, and other questions related to condensed matter, will occupy the group for the foreseeable future. The common thread will center on the study of ultracold atoms in various types of external potentials (disorder, periodic lattices, one, two, and three dimensions) in the presence of strong interatomic interactions. These interactions will often be accompanied by strong correlations and entanglement. These issues will be studied with increasingly sophisticated detection techniques, particularly with better and better atomic imaging, with respect to spatial resolution, speed, and quantum efficiency.

The theory component of the group also plans to follow a similar intellectual trend with special focus on the **dynamics of strongly-correlated quantum systems**. Complementary analytical and numerical studies will be conducted in parallel as far as possible. Sophisticated numerical computations will be further developed, making increasing use of local and national clusters.

Implanted as we are in an Institute devoted to many types of optics, our work will nevertheless maintain close contact with this field. We will continue to pursue problems in the field of atom optics, particularly those in which the roles of quantum fluctuations and entanglement are important. We will also continue our collaboration with Thales in the development of a prototype atom-chip based gravimeter.

Quantum Optics: perspectives

In the forthcoming years we plan to continue and develop the current experimental setups, in the framework of ongoing or future European projects. More precisely the projects are as follows.

For the "Atoms" part, we shall continue the exploration of systems of small numbers of interacting atoms, using two experimental setups. The common concept will be the **dipole-dipole interaction between atoms**. The general framework is therefore the study of model many-body systems where the interactions between the atoms are dipolar and therefore long-range. In Rydberg physics, arrays of ~ 10 microscopic dipole traps will be used to explore quantum simulation opportunities. In the other setup, with a dense ensemble of ~100 atoms, we shall explore the Dicke model in the presence of interacting atoms – a theoretically fairly challenging domain.

For the "Photons" part, we shall keep investigating the potentialities of either heralded or deterministic operations in quantum optics and quantum information processing. Our new setup on “giant” non-linear effects based on Rydberg atomes in a cavity will be further exploited to produce new quantum states of the light, as well as “logical operations” between photonic qubits, with theoretical studies to be conducted in parallel (EU project SIQS). Protocol fidelity for the khi(2) non-linearities in the femtosecond regime is a priority, with the perspective of efficient quantum memories and quantum protocols of increasing complexity, e.g. based on optical cavities with active insertion / extraction devices. Activities on Continuous Variable Quantum Key Distributions (CVQKD) will also be pursued, in collaboration with LTCI (Eleni Diamanti), IEF (Laurent Vivien, Delphine Morini), and SeQureNet.

Nanophotonics and Electromagnetism: perspectives

Perspectives of the NAPHEL group are organised around three axes:

“Nanophotonics of few photon systems”. This addresses quantum nanophotonics (notably with the HOM experiment) but also the engineering of efficient single-photon sources.

“Devices with novel nanophotonic physics”. This comprises electrical sources of surface plasmons, guided nanophotonics with inverse-rib structures, and systems that implement PT-symmetry.

“Thermal radiation nanophotonics”. This axis, addresses ambitious concerns such as “thermal transistors” and their use with novel materials such as graphene. It also has more direct applications through directional thermal sources. Energy and in particular solar energy management through these novel possibilities is a still underdeveloped perspective that could be tackled with interest in the next five years.

More development of inter-group activity will also be considered (Quantum Optics, biochips in the Biophotonics group, MANOLIA, Lasers).

Nonlinear Materials and Applications: perspectives

With the success of our demonstrations of nonlinear optics in liquid filled microstructured fibres and liquid immersed nanofibres, we are convinced by the benefits of these hybrid approaches. Combining the advantages of structured materials for confining and enhancing the light intensity, with another material selected on purpose for its optical nonlinearity opens new areas of research and applications.

Concerning the structured materials, we will expand our investigations to fibres made of new glasses and to silicon photonic crystal waveguides, such as silicon slot waveguides. In addition to liquids, we plan to use polymers, and carbon nanotubes embedded in polymers. With these new hybrid systems, we plan to investigate new functional devices such as sources, sensors and Brillouin based ultrasonic transducers for instance.

One of our strong axes will be the development of optical components for quantum telecommunication networks that uses the specific properties of these hybrid structures: sources of entangled photon pairs, single-photon frequency converters…

Concerning nonlinear SBN thin films, the limits of structuring the remnant polarization in these films using an atomic force microscope will be explored, and the realization of test SBN thin film devices such a modulators will be undertaken. In addition to these devices we would like to apply our knowledge to the realization of non-linear optical circuitry working on both temporal and spatial components of multimodal beams that are now found in the new multimodal optical channels in the area of optical communications.

We will also pursue our investigations in optical archiving trying to fulfil the challenging combination of long-term archival, ultra-large capacities and low energy consumption.

Biophotonics: perspectives

Our group will continue working on the physical study, development and characterization of optical systems for life science applications in collaboration with biologists. We will focus on merging modalities to develop unique set-ups able to address relevant biological questions.

We will study the fundamental aspects and development of a nano-micro-plasmonics based system capable of both quantification by Surface Plasmon Resonance Imaging and identification by Surface Enhanced Raman Spectroscopy of biochip binding events. Investigated applications concern early cancer diagnosis and food quality and safety control (ANR support has been granted).

We will further our studies on full-field OCT to achieve in situ endoscopic ultrahigh-resolution imaging of diseased tissues with improved detection sensitivity. Several complementary imaging modalities will be coupled to full-field OCT including nonlinear optical microscopy and elastography. Our super-resolution STED microscope will be adapted to neurobiology studies (Alzheimer's disease).

Our recent breakthrough on single eukaryotic ribosome dynamics opens the way to studies of many processes affecting protein translation fidelity. The combination of optical tweezers, Förster Resonance Energy Transfer and OCT will give us a multimodal approach to mechanotransduction studies on endothelial cells, for a better understanding of cardiovascular diseases.

Lasers: perspectives

For next years, the **Lasers group** will continue on the development of new **diode-pumped solid-state lasers** covering a broad range of gain media (crystals, fibers, semiconductors), temporal regimes (CW to fs) and wavelengths (UV to IR).

In order to demonstrate high energy, high average power short pulse amplifiers, we will combine novel gain medium architectures for a better thermal management such as **thin or thick active mirrors, slab and single crystal fiber** (SCF) with new Yb-doped **CaF_2 and CALGO** crystals. The **SCF** amplifier concept will be applied within the European **RAZIPOL** project for 100 W ultrashort amplifiers for material processing.

The installation of the front-end of the **Apollon 10 PW** laser is scheduled for the end of 2014. Based on our experience acquired on **OPCPA** systems, we will start an activity **in mid-IR few-cycle** Carrier-Envelope Phase (CEP) stabilized sources.

Coherent beam combining, as a way to scale the power/energy of laser sources, will be investigated in two contexts: with fs lasers through **pulse synthesis** (coherent combining of fs pulses with different spectra) and **cavity enhancement** (coherent combining of successive fs pulses); with high-power high brightness CW laser diode arrays in **passive and semi-passive architectures** within the European **BRIDLE** project. **Dual frequency optically pumped semiconductor lasers** will be used to drive a Cs Coherent Population Trapping atomic clock. New projects will start on **LED pumped solid-state lasers** and **pressure phase matching** for non-linear crystals to reach the UV band.

XUV Optics and optical Surfaces: perspectives

The XUV Optics group will pursue research in three main axes: XUV optical surfaces and systems, innovative multilayers for XUV optics and ultrashort pulses optics. The development of state of the art XUV optical systems requires very specific knowledge and know-how concerning polishing, aspherization, surface metrology and multilayer coating.

The XUV group will take advantage of its expertise in these domains in order to develop a **full field soft x-ray microscope** for biological applications. This instrument is part of the Equipex Morphoscope and will be developed in collaboration with synchrotron Soleil.

Further research for **efficient multilayer coatings** with specific properties in the X-ray and EUV domain is a technological key for several applications including space science, plasma laser diagnostics, synchrotron radiation sources and new generation sources (x-ray lasers and free electron lasers, high harmonic generation). Our effort will be mainly focused on small-period, low-roughness multilayers for x-rays and on optimization of aperiodic multilayer designs.

The **manipulation and characterization of ultrashort pulses** (in the femtosecond and attosecond regime) is a scientific and technological challenge. We will pursue the study and development of multilayer optics for atto-pulses and we will implement some innovative characterization methods to fully characterize (spatially and temporally) such pulses.

The XUV Optics group will benefit from the new platform “Couches Minces pour l’Optique X” that will be installed in Palaiseau building at the end of 2014, including a new deposition machine specifically design for x-ray multilayers (projet CeMOX, SESAME IdF 2012). One aim of this platform will be to develop new collaborations and/or transfers with industrial partners.

Imaging Sytems and Physics of Images: perspectives

The research domains addressed in the previous years have provided opportunities for both basic scientific contributions and industrial applications. They involve many interesting perspectives, and will continue to form the main lines of the strategy of SPIM team in the future.

- **Polarization imaging**: we have made original theoretical and experimental contributions, and gained good international visibility on this topics. The applications addressed so far were mainly related to defense, and our objective is to investigate new approaches and new application domains (navigation, biomedical, industrial control).
- **Modelling and control for adaptive optics (AO):** our team has developed and demonstrated innovative control methods based on physical modelling of AO systems (3D turbulence, mirrors dynamics, …). Building on these

achievements, our objective is to take an active part in the control design for future high-performance astronomical instruments on VLTs or ELTs, and to develop industrial applications, e.g. in the domain of retinal imaging.

- **Joint design of imaging systems and image processing algorithms:** the added value of our team in this very competitive domain is to possess skills in optical design and in digital image processing. We want to take profit of this position to investigate new methods of optical design, and innovative imaging architecture and modalities (e.g. 3D imaging).