

PROJET SCIENTIFIQUE DU LCFIO, UMR8501, POUR LA PERIODE 2010-2013.

Laboratoire Charles Fabry de l'Institut d'Optique (LCFIO) herewith applies for continued recognition, for the period 2010-2013, as a joint research unit* of Institut d'Optique – *Graduate School*†, Université Paris-Sud 11, and CNRS. This document is the scientific project for 2010-2013. In compliance with the instructions, the complete application document otherwise consists of

- the data spreadsheet associated to the present project,
- a set of individual reports by the scientists (faculty members, CNRS research scientists and research engineers) established in anticipation of January 1st, 2010 (in French)
- **the scientific report for 2004-2008 (in English)**
- the “bilan scientifique” data spreadsheet associated to the latter report,
- the associated list of scientific publications and other achievements,
- another set of individual reports by the scientists, in fact nearly identical to the former, but established as of June 2008 and therefore including the colleagues who are currently active in LCFIO and not those who are planning to join (in French)
- finally, data (in French) concerning
 - continuing education actions for the personnel,
 - the participation in teaching activities and in actions for the promotion of science,
 - and hygiene and security within LCFIO.

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* « unité mixte de recherche », UMR. LCFIO is listed as UMR8501.

† For an UMR with more than one Academic Institution among its partner institutions, an “établissement de rattachement support” should be appointed. In this case, that would be Institut d'Optique – *Graduate School*.

SCIENTIFIC PROJECT

CHAPTER 1 - INTRODUCTION TO THE SCIENTIFIC PROJECT

1.1 – A CHANGING CONTEXT

As already said in the “scientific report” section, LCFIO is at this time the only research unit officially recognized at the national level inside “Institut d’Optique – Graduate School” (IO-GS). It is therefore a central piece of this “Optics College”, a unique case in France devoted to master level teaching in optical science and engineering and research in Optics. The context, however, is changing, locally, nationally and internationally.

At the scale of the Greater Paris Area (Région Ile de France and, as far as IO-GS is concerned, Département de l’Essonne), the increased support to research has already been mentioned. The significant impact on our research from the initiatives Triangle de la Physique and IFRAF (Institut Francilien de Recherche sur les Atomes Froids) has been outlined in the scientific report. Since mid-2008, Opération Campus, a national initiative to modernize selected University Campuses, has labelled the neighbourhood of “Plateau de Saclay”, including Palaiseau and Orsay, as one of its priorities. An improvement of the facilities available for higher education and research, together with better urban infrastructures, can be expected. It will favourably impact our environment. In September 2008, construction has been started for the extension of the IO-GS building in Palaiseau. At the beginning of 2010, very likely, the whole LCFIO will therefore be re-united geographically in one single building, and some space may be available for future initiatives. Those initiatives might concentrate on research and/or prioritize closer interaction with industry and the promotion of economic development, but in any case LCFIO should have opportunities to be involved. An implication is that LCFIO should retain its specificity as a joint research unit between IO-GS, CNRS and Université Paris-Sud 11. That does not preclude, on the contrary, maintaining close links with other institutions and in particular other laboratories active in similar domains – optics, atomic and molecular physics, nanosciences and nanotechnologies – in its surrounding and remaining an active member of coordination initiatives such as Triangle de la Physique and Fédération Lumière et Matière.

At the national scale, for five years already an annex of IO-GS has been operating at Saint-Etienne, in the Rhône-Alpes region. A plan for expanding the annex is currently being elaborated, including a new research initiative in association with Laboratoire Hubert Curien (CNRS/Université Jean-Monnet, Saint-Etienne). In addition, contacts are well underway for an additional annex with its own research laboratory in Bordeaux. Therefore, in the near future, LCFIO will no more be the only research laboratory at Institut d’Optique. The coordination of research in the IO-GS might imply establishing a Scientific Advisory Committee for IO-GS, a concept that never existed exist until now at IO-GS but would be appropriate in that context. As opposed to the LCFIO internal committee (conseil de laboratoire), whose continued necessity is beyond question, that Scientific Advisory Committee would consist exclusively of external appointed scientists.

It is appropriate to compare the situation of LCFIO within IO-GS to similar laboratories internationally. It has already been mentioned in the scientific report that, as far as research indicators are concerned, IO-GS can sustain the comparison with research at the three institutions in the USA where graduate level education and research in optics are combined. Nowadays, a strong need is expressed by some industrial companies in Europe for an increased number of Optics graduates at the master level, and initiatives have developed at many places: Jena, Karlsruhe, Erlangen, Barcelona. IO-GS has already taken the initiative to coordinate an international “Erasmus Mundus” master course together with partner universities in Delft, Jena, London and Warsaw, that complements the “Erasmus Mundus” offer in Photonics by Gent, Brussels, Saint-Andrews, Edinburgh (Heriot-Watt University) and Stockholm. Indeed, worldwide, these and other Optics centres are benefiting from favourable local and national conditions, just as IO-GS, allowing them to initiate new developments and to increase their size. It is important for IO-GS to keep and strengthen its recognition as one of the main academic institutions in Optics in Europe and that might at some point imply a new policy of international partnerships in research. However, in the near future, the priority at LCFIO will remain a strong presence in the EU Framework Programmes, a policy that has been essential for its achievements in the last ten years or more.

To summarize, IO-GS is in a position to increase in size, better cover and better serve Optics research and graduate education. That is true also for its component LCFIO, in its geographical surrounding of Palaiseau-Saclay-Orsay.

1.2 – PROMOTING NEW RESEARCH PROJECTS AND NEW RESEARCH TOPICS

Under this heading, laboratories are invited to describe their policy for encouraging risk taking in research and venturing on topics at the limits of the disciplinary fields. Essentially, research in the kind of fields covered by LCFIO is mostly carried out by small teams with two or three senior scientists and about the same number of doctoral students. Therefore, the scale of the LCFIO groups where two to five such teams work on related subjects is in our opinion appropriate to encourage truly original research in the fields covered by the groups, provided that the group leader has a fertile imagination and is ready to take risks. By risk taking, we mean here embarking on subjects that might lead to a completely unexpected result or to no result at all. Funding agencies are known for their tendency to shy away from such subjects, which is also understandable because as long as a subject is ill-defined and has a high risk to lead nowhere, a reliable reviewer should also warn the agency

of the risk, thus decreasing the ranking of that application. Therefore, the best options for risk taking appear to us on the one hand, to hire bright individuals who will not just tend follow more or less straightforward paths, and on the other hand to do our best to relax the administrative constraints on reporting to the funding agency about the use of every single euro spent within their funded project so that part of the funds of one project can in fact be used to initiate the next good idea. The latter is unfortunately not politically correct and also not really in the hands of the laboratory director. On the former, it is appropriate to cite the following statistics: during 2004-2008 (inclusive), LCFIO was fortunate enough to hire 14 new faculty or research faculty members. Of these, only three had obtained their doctoral degree at LCFIO. Those three had stayed in one or several other laboratories for post-doctoral research, and in only one case was the post-doctoral period shorter than two years.

We conclude from the above that LCFIO expects well thought and innovative research to result from the groups' prospective plans as developed in chapter 2 through 7 of this report, and we are left with the issue of topics not currently covered by the groups. On those, the role of the laboratory is essential. Some general thoughts will be developed below, but the main issue is that research topics at IO-GS are expected to evolve automatically through the current opportunities at Saint-Etienne and even more Bordeaux, which may directly impact LCFIO. Also, as already mentioned, LCFIO may enjoy the opportunity to slightly expand in size, but – this sentence being written in agreement with the Director General of IO-GS – that will not happen unless new topics are introduced. In that respect, the proposed IO-GS Scientific Advisory Committee will have an important role to play. Its existence will also ease the internal discussion process when new profiles have to be defined for new research scientist positions, at least for faculty members since the CNRS scientist positions are defined centrally by the CNRS leadership.

Turning now to a few specific topics, it seems generally appropriate to highlight and strengthen our activities in the core of the Triangle de la Physique priorities: the quantum physics subjects (Chapters 2 and 3), nanoscience and nanotechnologies (essentially all chapters with 100% of Chapter 4), our participation in the Institut de la Lumière Extrême / Extreme Light Infrastructure (Chapter 6 and parts of Chapter 7), and X Ray Optics (Chapter 7). An initiative by Triangle de la Physique on the take up of research results is announced for the end of 2008 and also corresponds to a need at LCFIO, see subsection 1.3.

Concerning XUV Optics, new generation soft X-ray sources and XUV optics instrumentation is a clear strength of the “Saclay” environment. A new initiative, in partnership with our colleagues from Université Paris-Sud 11, CEA, Ecole polytechnique, ENSTA could be generally beneficial and open opportunities for introducing new topics, currently not covered in the environment.

The “Saclay” environment enjoys good facilities in terms of clean rooms for nanotechnology processes, and we hear that Laboratoire de Photonique et Nanostructures and Institut d'Electronique Fondamentale, currently the hosts of two large facilities, may have an opportunity to join and expand their equipment. In this favourable situation, it is essential that LCFIO remains active in the field of nanostructures fabrication and the resulting devices, using the equipment of those two clean rooms when appropriate, and also investing more time and effort from doctoral students, but also from one or two permanent scientists, in its own equipment, shared with Ecole polytechnique and Thales Research and Technology. Indeed, direct access to facilities is essential for device research. An investment plan in new equipment will be discussed with our partners in the coming few months.

Our skills in optical metrology, optical system design, optical polishing and aspherisation are currently threatened by insufficient manpower and by the retirement of knowledgeable and reliable technicians and engineers. What to absolutely maintain, and for which scientific purposes, will be a political decision that needs to be taken in the coming two or three years. That will imply introducing new subjects and hire new faculty and staff. Aside the further development of XUV optics, which is greedy of high quality optical workshop services, one option is to increase and highlight the expertise of LCFIO in terms of modelling. Modelling skills of various kinds – optical design, electromagnetic optics, non linearities, laser dynamics – are distributed throughout the laboratory, and also on big demand. Needs for modelling activities arise in most of our research groups and most of the external request for cooperation involve modelling, in particular from industrial companies not related to optics who perceive needs for optical expertise. Some aspects of modelling in relation with signal processing, in addition to those already addressed in Chapter 7, could be introduced.

As opposed to the group prospective thoughts developed in Chapters 2 through 7, which are fairly precise, the possible initiatives hinted at in the above paragraphs are still vague and will require discussion within LCFIO. Indeed, at a recent meeting of all faculty and research faculty members for the preparation of the present “scientific project” document and its companion “scientific report”, the need was stressed to introduce some systematic opportunities for scientific discussions involving representatives of all groups. That would come in addition to the general seminars, where open discussion is possible, but where the conditions for strategic planning are not met. The internal laboratory committee (Conseil de Laboratoire) should be one instrument for the debate. The idea to regularly discuss at the Conseil de Laboratoire meetings of recent proposals (whether successful or not) submitted to funding agencies was proposed as one approach.

Board of Governors (Conseil d'Administration): President: Elisabeth Giacobino				
General Director: Jean-Louis Martin				
<p>Education J.M. Jonathan</p>	<p>Research: Christian Chardonnet</p> <ul style="list-style-type: none"> • Coordination of research at Saint Etienne • New laboratory to be established at Bordeaux • Laboratoire Charles Fabry de l'Institut d'Optique 	<p>Administrative and financial Director Annie Montagnac</p>	<p>Director for Valorisation and Industrial Relations Bernard Laloux</p>	<p><i>Services attached to the General Director</i></p>
	<p>Research groups and teams</p>	<p>Technical services</p>		
<ul style="list-style-type: none"> • Master in Optical Engineering programme • Master of science programme • School administration and student affairs 	<p>Atom Optics (chap 2), Alain Aspect</p> <ul style="list-style-type: none"> • Quantum Atom Optics and nanomanipulation of atoms, Christoph Westbrook • Coherent Atom sources and atom interferometry, Ph. Bouyer 	<ul style="list-style-type: none"> • Electronics • Modelling • Optical workshop • Mechanics: <ul style="list-style-type: none"> • Technical design and drawing • Mechanical workshop • Metrology • Clean room facilities • Instrumentation 	<ul style="list-style-type: none"> • Financial affairs • Accounting • Personnel management • General affairs • Service intérieur • Photocopying • Library (médiathèque) 	<ul style="list-style-type: none"> • IOTech ingénierie (research partnerships with industry) • Continuing Education • Education by apprenticeship • Valorisation and Intellectual Property
	<p>Quantum Optics (Chap 3), Philippe Grangier</p>			
	<p>Nanophotonics and Electromagnetism (Chap 4) Henri Benisty, Jean-Jacques Greffet et Philippe Lalanne</p>			
	<p>Nonlinear Materials and Applications (Chap 5) Gilles Pauliat</p>			
	<p>Lasers and Biophotonics (Chap 6) Patrick Georges</p> <ul style="list-style-type: none"> • Solid State Lasers and Applications, Patrick Georges • Materials, Components and Systems for Biophotonics, Michael Canva 			
	<p>Optical Systems and Components (Chap 7), Pierre Chavel, Raymond Mercier</p> <ul style="list-style-type: none"> • XUV Optics, Franck Delmotte • Imaging systems and Physics of Images, Jean Taboury 			
			<ul style="list-style-type: none"> • Computing and Networking Services • Communication • Construction • Maintenance, infrastructure • International relations 	

Organisational chart 1: LCFIO within its host institution, Institut d'Optique – Graduate School

CNRS researchers		Faculty			Age	born	CNRS engineers and technicians							
	Roosen				64	1944	Lamare							
Jogeux	Frey				63	1945	Roger Gi.							
					62	1946	Rodier	Bridou	Desvignes	Roger Gé.				
	Aspect				61	1947	Abrial	Aide	Allain M.	Clotaire	Fournet		Ravet	
					60	1948	Colas							
		Taboury			59	1949	Hoffeurt				IOTA		IATOS/ITARF	
	Chavel	Hugonin	Jonathan		58	1950	Bellemain	Vergilino						Druesne
					57	1951								
		Mercier			56	1952					Armand			
	Cuniot-P				55	1953								
					54	1954	Villing							Duong
		Varnière			53	1955					Bellart			
					52	1956								Ea Kim
	Grangier				51	1957								Canale
Westbrook	Pauliat				50	1958					Laloux			
					49	1959	Mangeon	Beurthe			Le Boudec	Robin		Théneau
					48	1960	Moron	Montagnac						Pereira
		Sauer			47	1961					Tcherniavsky			
	Georges				46	1962								
Lalanne	Carva	Benisty			45	1963	Cadoré							
					44	1964	Besbes				Seychelles			Roth
	Delaye	Westbrook			43	1965	Edwards							
					42	1966					Avignon-V			
					41	1967								
		Messin	Balembois		40	1968	Guédon							
	Bouyer	Boiron	Dubois		39	1969	Fuchs							Vigne
		Tualle Brouri	Dubreuil	Goudail	38	1970	Salou							
		Lucas-Leclin			37	1971	Baudry							
Druon	Browaey	Delmotte			36	1972								
	Bouchoule				35	1973								
	Hanna	de Rossi	Sortais		34	1974								
Cambournac	Sanchez-P.	Josse	Lebrun		33	1975	Leclercq	s.gx techniques 13						
	Arnaud				32	1976	Abdoulahyane	groupes 9 personnes			Martins			
	Péronnet	Moreau			31	1977	Jérôme	gestion administration 21			Chedorge			
					30	1978		infrastructure 4			Perrot			50 persons
Bourdel	Sauvan	24 c	22 ec					IOTech DREV 4			Capmas			not all full time

Age pyramid
end of 2007
small font: retirement 2008

CNRS researchers		Faculty			Age	born	CNRS engineers/technical staff							
	Frey				65	1945								
					64	1946	Bridou							
	Aspect				63	1947	Clotaire							
					62	1948	Colas							
		Taboury			61	1949				IOTA		IATOS/ITARF		
	Chavel	Hugonin	Jonathan		60	1950	Bellemain	Vergilino				Druesne		
					59	1951								
		Mercier			58	1952					Armand			
	Cuniot-P				57	1953								
					56	1954	Villing					Duong		
		Varnière			55	1955					Bellart			
		Age pyramid previsions 1.1.2010			54	1956	Guilbaud					Ea Kim		
Chardonnet	Grangier						53	1957						Canale
Westbrook	Pauliat						52	1958					Laloux	
		Greffet	recruiting 2008 et retirements 2009 included, without assumption regarding recruiting in 2009		51	1959	Mangeon	Beurthe	Le Boudec	Robin		Théneau		
					50	1960	Moron	Montagnac					Pereira	
		Sauer			49	1961								
	Georges				48	1962								
Lalanne	Carva	Benisty			47	1963	Cadoré							
			46	1964	Besbes							Roth		
	Delaye	Westbrook			45	1965	Edwards							
					44	1966					Avignon-V			
					43	1967								
		Messin	Balembois		42	1968								
	Bouyer	Boiron	Dubois		41	1969	Fuchs							
		Tuaille Brouri	Dubreuil	Goudail	40	1970	Salou							
		Lucas-Leclin			39	1971	Baudry							
Druon	Browaeyts	Delmotte			38	1972								
	Bouchoule				37	1973								
	Hanna	de Rossi	Sortais		36	1974								
Cambournac	Sanchez-P.	Josse	Lebrun		35	1975	Leclercq	s. gx techniques 13			Martins			
	Arnaud				34	1976	Abdoulahyane	groupes 2 personnes			Chedorge			
	Péronnet	Moreau	Marquier		33	1977	Jérôme	gestion administration 15			Perrot			
Bourdel	Sauvan				32	1978		infrastructure 3			Capmas	37 persons		
	Laroche	24 c	24 ec		31	1979		IOTech DREV 4				not all full time		

1.3 – INNOVATION AND INDUSTRIAL PARTNERSHIP

All groups have industrial partners. Industrial partnerships during this period have involved large groups – Thales, Sagem, Osram, Essilor, Saint-Gobain – and SMEs – Amplitudes Systèmes, Genoptics (a 2001 startup company that originated from LCFIO research results), Genewave, Cristal Laser, Imagine Eyes, Laserlabs, Optrion, Oxxius, Eolite, Fibercryst, Xenocs. Partnerships involved joint patents, scientific consulting, patent licencing, and CIFRE doctoral support. Indeed, about 20% of the doctoral student fellowships are through industrial partnerships. Industrial partners are involved in joint projects funded in part by the European Union and by ANR. Indeed, IO-GS has been awarded the “Institut Carnot” in recognition of its relatively strong involvement in industrial partnerships. However, the fraction of funding directly paid by industry is low, and during the evaluation of the “Carnot” activity, the committee has criticized the limited involvement of scientists in promoting more partnerships of the kind that would increase that fraction.

It is likely that industrial partners are more ready to participate in collaborations with our groups on upstream subjects far ahead from the competitive domain, and that they expect to see supported by public funds. On the other hand, they may be ready to fund research activities closer to their competitive strategy. When that happens, and when the specific request happens to fall exactly inside the current domains of interest of one of the groups, that group will most likely respond positively. But in many cases, the requests from industry relate to the skills accumulated at IO-GS rather than to the current research activities. To a fair extent, IOtech, the partnership division of the IO-GS department for industrial relations, has tried to deal with those requests if financially viable terms could be found with the partner, but more should be done in that direction. In the same vein (and although, public funds are available for well evaluated projects), LCFIO has not until very recently participated in research actions supported by the “Poles of Competitiveness” labelled by the French government, and that in spite of the fact that IO-GS is a member of the Pole of Competitiveness on complex systems, “System@tic”. As has already been suggested, most opportunities for industrial collaborations at the request of the industrial partner, as opposed to those emerging from common upstream research directions, relate to modelling or at least include a significant fraction of modelling. This is one reason to promote a strong optical modelling component among the LCFIO Engineering Support departments (see subsection 1.4.3 below). One problem is that such collaborative projects may or may not easily lead to publications and may or may not be consistent with the research strategy for the LCFIO members involved. It is therefore likely that more positions for research engineers will need to be opened and funded by those future industrial partnership projects. While these positions will not be permanent positions paid directly by CNRS or the Ministry in charge of Higher Education, means have to be identified to make them attractive and to retain some high quality scientists.

The issue of Intellectual Property policy should be raised at this stage. In fact, LCFIO is satisfied with the current policy, where any opportunity for protecting Intellectual Property through patents is handled by CNRS. After examination of the case and, as appropriate, negotiation with the outside partners if any are involved, CNRS will contact the other two founder institutions of LCFIO, IO-GS and Université Paris-Sud 11, for possible joint ownership of the rights. The net result is that most of the patents filed following LCFIO inventions are either the property of CNRS or jointly owned by CNRS and industrial partners.

1.4 – ORGANISATION

1.4.1 – ORGANISATIONAL CHART

See the previous pages for the organisational chart. The two pages following the organisational chart show the evolution of personnel and in particular of technical staff between the end of 2007 and, as can be predicted at this stage, the beginning of 2010. They will be commented upon in subsection 1.4.3.

1.4.2 – ADMINISTRATION, INFRASTRUCTURES

Direction du laboratoire:

Director: Christian Chardonnet, directeur de recherche
Assistant: Nathalie Baudry, technicien, CNRS
European Project Manager: Benoît Plichon, ingénieur d'étude, IO-GS
Professor Emeritus : Alain Brun

Direction administrative et financière

Director: Annie Montagnac, ingénieur de recherche, since January 2008

Financial affairs, accounting and personnel:

- Abdelaaziz Aboulahyane, technicien, CNRS
- Jocelyne Armand, assistant-ingénieur, IO-GS
- Christine Avignon-Vérité, assistant-ingénieur, IO-GS
- Ghislaine Canale, adjoint technique, enseignement supérieur
- Audrey Chedorge, assistant-ingénieur, IO-GS

- Nicole Estèves-Mangeon, adjoint technique, CNRS
- Hasna Mernit, assistant-ingénieur, IO-GS
- Catherine Salou, ingénieur de recherche, CNRS, since February 2008
- Isabelle Soury
- Ghislaine Théneau, agent technique, enseignement supérieur

Service intérieur:

Marie-Hélène Bellart, adjoint technique, IO-GS
Christine Bruneau, technicien, IO-GS
Graça Martins, technicien, IO-GS

Library:

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

Computer services

Head: vacant position (anticipated for 2009)
Laurent Leclercq, assistant-ingénieur, CNRS

Communication

New person in charge of communication to be appointed.

Building, infrastructure

the Director General for the new building of Institut d'Optique
Head of infrastructure: Jacky Robin, ingénieur d'études, IO-GS
Jean-Luc Cadoré, assistant-ingénieur, CNRS
Daniel Druesne, technicien, IO-GS.

1.4.3 – THE ENGINEERING SUPPORT DEPARTMENTS

As said in the “scientific report” document and as is visible from the two age pyramids on the preceding pages,, the vast majority of the engineers and technicians active in the groups has retired recently or will retire before 2010. There is therefore both a need and an opportunity to organise engineering support within LCFIO as a common department, ideally under an appointed coordinator. The current members of the engineering support departments who are not expected to leave before 2010 are listed below, and the problems raised by departures are highlighted. One possible mode of operation would be the following. 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 reorganization of shared engineering support services has started with that model in mind and should be pursued, but it is clear that effort will be needed from all those involved to make that mode of operation a success. Engineering support will at this stage remain under the responsibility of the Director of LCFIO and of Raymond Mercier, Maître de Conférences, until a coordinator can be coordinated.

1.7.1 – Clean room facilities

Buntha Ea-Kim, ingénieur d'études, enseignement supérieur
Arnaud Jérôme, assistant-ingénieur, CNRS (part time)

The need for at least one additional engineer is obvious.

1.7.2 – Optical workshop

Person in charge: Gilles Colas, ingénieur d'études, CNRS
Jean-Yves Clotaire, assistant-ingénieur, CNRS
Christian Beurthe, technicien, CNRS

A new generation of polishers will need to be recruited, as two of the three current members will be 62 or more in 2010.

1.7.3 – Mechanical design and fabrication

Person in charge: André Guilbaud, ingénieur d'études, CNRS (since June 2008)
Mechanic workshop: Patrick Roth, adjoint technique, enseignement supérieur

The only full time draftsman will retire before 2010, hiring a new draftsman is currently the first priority of LCFIO as soon as a new person in charge of computer and network services has been recruited. The issue of whether or not to hire one more person full time at the mechanic workshop and thereby decrease the burden and cost of subcontracting should be addressed as well.

1.7.4 – Metrology

Christiane Vergilino, technicien, CNRS.

Here also, retirement of the only person specialized in metrology will need to be addressed and the continuity of some metrological capabilities will unavoidably be questioned.

1.7.5 – Electronics

Alain Bellemain, ingénieur de recherche, CNRS, currently mostly with group Laser et Biophotonique

Frédéric Moron, technicien, CNRS, currently mostly with group Optique Atomique

André Villing, ingénieur de recherche, CNRS, currently mostly with group Optique Atomique

1.7.6 – Instrumentation

Florence Fuchs, ingénieur de recherche, CNRS, since January 2008, currently mostly with group Optique Quantique.

It would be very helpful to hire a laser specialist. That would currently constitute the third priority (after those mentioned above).

1.7.7 – Optical design and modelling

Mondher Besbes, ingénieur de recherche, CNRS, currently mostly with group Nanophotonique et Electromagnétisme

The only modelling engineer specializes in electromagnetic optics and in the software implementation on computing clusters. Optical design is only covered as one side skill by a number of members of LCFIO, which is an issue for concern. As highlighted above, one ambition currently under discussion is to create, in coordination with the department of industrial relations at Institut d'Optique and its industrial research partnership division IOTech, a larger modelling division for service to the research groups and to the outside.

1.5 – FINANCES AND INVESTMENT

Recent budgetary data are available from the Excel spreadsheet associated with the “scientific report” document. Using 2007 figures, public permanent salaries amount to round 4 million euros. Other funds available to LCFIO likewise carry 4 million euros. Of these, 500 000 euros correspond to subventions from the Ministry of Research and from CNRS under the current 4-year contract (2006-2009). The remaining 3.5 million euros are obtained through proposals submitted in reply to calls from research funding agencies, mostly the European Union through the Framework Programme (FP, 900 000) and the French National Agency for Research (ANR, 800 000). Contracts from other national agencies and support from local governments (Région Ile de France and Conseil general de l'Essonne) follow. Funds directly paid by industry hardly reach 50 000 euros.

Until now, over 200 000 euros from the 4-year contract were transferred to the groups, and the rest was used centrally to cover the share of common costs of IO-GS devoted to research: administrative costs, fluids and technical services. In addition, as a necessary complement to balance those common costs, a nominal 25% deduction from the proposal funding was retained centrally, with various cases of exemptions, and the groups could use the rest to cover their direct research expenses. While these rules allowed to essentially balance the budget year after year, there was a strong feeling that the distribution of the 200 000 euros among the groups and the deduction exemption rules were arbitrary and outdated, therefore clarification is now needed.

In the current situation of research funding in France, it is safe to assume that the fraction of our funding that will need to be secured through proposals in reply to calls will increase even further. This is even more true if, as expected, some growth of the research staff and of the industrial collaboration activities can occur. Unless French and European funding agencies can offer a higher fraction of overhead than has been the case hitherto, it is likely that the exemptions will need to be decreased to keep a balanced budget, therefore there is an urgent need for an internal discussion to find rules that can be considered by all as fair.

Investment in equipment of common interest has been significant in the last few years with the PRISME metrology equipment funding, the clean room nanostructures process equipment (electron beam lithography equipment) and the replacement of all gas lasers with diode pumped solid state lasers. The next major need for equipment of common interest appears to be further investment in clean room equipment. Plans will be discussed with our partners TRT and Ecole polytechnique early in 2009.

1.6 – COMMUNICATION

LCFIO is regularly present in activities for the dissemination of scientific knowledge. Every year, it participates in the national Fête de la Science through three open house days at Institut d'Optique and through a scientific exhibit in a nearby exhibition hall. LCFIO significantly contributed a travelling exhibition on the scientific achievements of Gabriel Lippmann on the occasion of the hundredth anniversary of his Nobel Prize on interference colour photography; it is planned to start its journey in the middle of 2009. Some LCFIO scientists are regularly invited to present conferences to the general public, e.g. at

the Cite des Sciences de la Villette. Others are in charge of distributing throughout France an educational kit on micro-optics (diffractive optics and micro-lenses) designed and fabricated under the FP6 Network of Excellence on Micro-Optics NEMO.

1.7 – ACRONYMS

In the following chapters, some acronyms were deemed useful. They mostly are explained here. Since most of them correspond to French denominations, an approximate equivalent in English is provided when appropriate.

Positions

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 LCFIO are from Université Paris Sud 11 with teaching duties at Institut d'Optique*

Doctoral support

Allocataire	doctoral research fellow from the Ministry in charge of Research
AMN allocataire moniteur normalien	“allocataire” with teaching assistant position (applies to selected Ecoles Normales Supérieures graduates)
AMX allocataire moniteur polytechnicien	“allocataire” with teaching assistant position (applies to selected Ecole polytechnique graduates)
BDI bourse de doctorat pour ingénieurs	doctoral research fellowship from CNRS, in many cases partly supported by other funds.
CIFRE convention industrielle de formation par la recherche en entreprise	doctoral research position funded by industry with partial support from the government as part of a collaboration agreement between an industrial institution and the academic laboratory
DGA allocation de thèse de la Délégation générale pour l'Armement	in the doctoral support section, this acronym means “doctoral research fellowship funded by the Ministry of Defence Directorate for Weaponry.”
Cotutelle	Doctoral research work pursued at two places according to an agreement between the two universities involved.

Miscellaneous

ANR	Agence Nationale de la Recherche	French National Research Funding Agency
Cnano	CNRS coordinated actions for “nano” domain research	
CEA LETI	The Technology department of CEA, a French research organization	
CNRS	Centre National de la Recherche Scientifique	the major National Organisation conducting research and, to some extent, funding research projects
DGA	Délégation générale pour l'Armement, the Ministry of Defence Directorate for Weaponry.	
EC	European Commission	
ESPCI	Ecole Supérieure de Physique et de Chimie Industrielles, Paris	
FP	Framework Programme for Research and Technical Development of the European Commission	
GdR	Groupement de Recherche	CNRS specialized group established to foster a given topic
HdR	Habilitation à diriger les recherches	Highest academic degree in France
ICSN	Institut de Chimie des Substances Naturelles, CNRS, Gif-sur-Yvette	
ICT/FET	Information and Communication Technology, Free and Emerging Technologies	
IEF	Institut d'Electronique Fondamentale, CNRS and Université Paris-Sud 11, Orsay	
IP	Intellectual Property	
LNE	Laboratoire national de métrologie et d'essais -	The French national laboratory for time and frequency

SYRTE	Système de Références Temps-Espace	standards
LOA	Laboratoire d'Optique Appliquée, CNRS / Ecole polytechnique / ENSTA, Palaiseau	
LPN	Laboratoire de Photonique et Nanostructures, CNRS, Marcoussis	
ONERA	“the French Aerospace Lab”	
STREP	EC funded topical research action	
TRT	Thales Research and Technology	

CHAPTER 2 – FUTURE PROSPECTS OF THE ATOM OPTICS GROUP³

Head: ASPECT Alain

Directeur de Recherche

Faculty and Research Faculty holding permanent positions:

BOIRON Denis	Maitre de Conférences
BOUCHOULE Isabelle	Chargé de Recherche
BOURDEL Thomas	Chargé de Recherche
BOUYER Philippe	Directeur de Recherche
JOSSE Vincent	Maitre de Conférences
PERRONET Karen	Chargé de Recherche
SANCHEZ-PALENCIA Laurent	Chargé de Recherche
WESTBROOK Chris	Directeur de Recherche
WESTBROOK Nathalie	Professeur des universités

Engineers, technicians holding permanent positions (seconded more than half time from the engineering support department)

VILLING André	Ingénieur de recherche
MORON Frédéric	Technicien de recherche

Doctoral students already present at the time of this writing and who not expected to graduate before the end of 2009

ARMIJO Julien	Allocataire, 2007
BERNARD Alain	DGA, 2007
BERNON Simon	AMX, 2007
BONNEAU Marie	Allocataire, 2008
GEIGER Rémy	AMN, 2008
HAMBRECHT Ben	Allocataire, 2007
JASKULA Jean-Philippe	Allocataire, 2007
LE GALL Antoine	Allocataire, 2008
ROBERT de ST VINCENT Martin	AMN, 2007

³ See list of acronyms and explanations page 10

2.1 – PROSPECTS OF THE ATOM OPTICS GROUP: AN OVERVIEW

Since its start in 1992, the atom optics group has developed a line of research based on the *analogy with photon optics* (rays optics, wave optics, coherent optics, non linear optics, quantum optics). With the strong background in AMO physics of all the members of our group, and our situation amid the broad expertise present in Institut d'Optique, it would be a fault not to pursue that line. *Atom interferometry* is on the agenda for ultra sensitive measurements of inertial and gravitational effects, with applications ranging from basic research (tests of general relativity in space) to technology (navigation or underground sensing) and our group will be present in both research lines. We will take advantage of the preindustrial structure IOTECH at Institut d'Optique, and of our natural relation to industry, to develop reliable instruments, with the hope that they could be useful to other labs, and possibly find a market. These prospects raise several fundamental questions, which we want to address. Is it possible to make a reliable atom interferometer on an atom chip, in spite of the lack of decoupling of the atoms from the noise coming from the substrate? Is it possible to use an atom laser for an atom interferometer, in spite of the non linear effects associated to atom-atom interactions, which can lead to uncontrollable phase shifts? This huge non-linearity, analogous to a Kerr non linearity in photon optics but larger by orders of magnitude, could in fact lead to spectacular effects in *quantum atom optics*, as number squeezing, or the production of entangled beams of atoms. Heisenberg limited interferometry, with a sensitivity beyond the standard quantum limit, should become possible. A first elementary but spectacular example of the production of “non-classical” states in the sense of quantum optics would be interaction blockade in a resonant atomic cavity to develop a source of single atoms, delivered one by one. Our horizontal atom laser appears as a privileged tool to for this project. On the other hand, atom chips combined to optical resonant cavities are attractive systems to develop tools for quantum information, such as quantum gates. Our efforts, in collaboration with LPN, to develop an integrated opto-atomic chip is risky, but in case of success it offers the prospect of “easy” scaling.

An already successful facet of our activity in *quantum atom optics* is the metastable helium program, which takes advantage of our unique *time and space resolved single atom detector* to measure atom-atom correlation functions, a fundamental quantity in quantum optics as shown by R. Glauber fifty years ago. We will continue to explore the analogy with milestones experiments in quantum photon optics. Evidence of entanglement by Bell's inequality violations, or of the Hong Ou Mandel effect (boson coalescence on a beam splitter), would be major breakthroughs in quantum atom optics. We will also explore the new dimension of quantum optics offered by the possibility to use ^3He –a fermion, rather than ^4He –a boson.

Since the discovery of dilute Bose-Einstein condensates in 1995, it has become more and more clear that these systems allow one to revisit standard problems of *condensed matter*, with unique possibilities to vary parameters as interaction strength, tunneling, density, temperature. It becomes then possible to test standard condensed matter models in situations impossible to achieve in the case of electrons in a solid or of liquid helium. Moreover, the variety of observation tools available with cold atoms, (from in situ observation of atomic density to time of flight measurements of velocity distribution, Bragg spectroscopy, etc...) opens fully new possibilities. Our first observation of Anderson localization of a 1 dimension non interacting boson can be put in that context, and we have a full program of exploring localization in 2D or 3D geometries, with controlled interactions, i.e. situations where theory is far from being completed. In this context it is also crucial to master *fermi atoms quantum degenerate gases*, and our new apparatus with mixtures of ultracold ^{40}K and ^{87}Rb will give us an access to these situations. Anderson localization of fermions will be studied in that apparatus. With the availability of $^3\text{He}^*$ and with the addition of optical lattices which is underway, our metastable helium apparatus will also explore these questions taking advantage of the unique probes (compared to alkali atoms) constituted by our single atom detector, or by the possibility to monitor the Penning ions current. Here again, the goal is to explore still open condensed matter problems, such as *strongly correlated fermions*. *Atom chips* are another possible approach to strongly correlated quantum degenerate gas, as already demonstrated in our group, and we will pursue that line. More generally, this whole line of research can be put in the context of *quantum simulators*, where clouds of ultracold atoms in optical lattices and with controlled interactions allow AMO physics to shed a new light on open questions of condensed matter.

Theory is a very important component of all these studies, and although each experimental team has a degree of theoretical expertise, it is a real asset of our group to have a *theory team closely interacting with the experimentalists*. The fruitful dialogue on Anderson localization will continue, with exciting new problems when we go from 1 to 2 or 3 dimensions, and take into account interactions. Our experimental program on fermion-boson mixtures will demand a support from the theory team. But it must be stressed that the theory team has also its own *independent projects*, as the one on spin glass and quantum magnetism. It is hoped that this project will eventually lead to new experiments, but at this stage it has its own momentum.

Finally, this overview of our projects cannot avoid addressing the question of the future of the biophotonics team. The scientific goal is ambitious and difficult: it consists of combining single molecule observations with optical manipulation to study ribosome dynamics. Its interest has been clearly established by international evaluations. Significant intermediate results are expected not later than early 2009, but the completion of the project will take longer, and the biophotonics team can continue for some time to benefit from the logistical, technical, and funding facilities of the atom optics group. In the long term however, this team will have to separate from its “surrogate mother”, and this will request an increase in size, for instance by attracting a scientist with a good expertise in biophysics. Whatever solution emerges, it should take into account the necessity of a tight collaboration with a biology team located as closely as possible. Openings in the biology department of Ecole Polytechnique may offer such opportunities.

2.2 – PROJECTS OF THE TEAMS

2.2.1 COHERENT ATOMIC SOURCES AND ATOM INTERFEROMETRY (P. BOUYER, THOMAS BOURDEL, VINCENT JOSSE)

Coherent atomic sources and atom interferometry hold the promise of applications as inertial sensors, for high accuracy measurements in applied or fundamental physics. The perspective of well controlled coherent atomic sources (atom laser) widens the spectrum of opportunities. Nevertheless, important issues remain to be answered: What is the ultimate limit of measurements based on atom interferometers? Is it possible to use an atom laser and how will interaction induced non-linear phenomena affect the accuracy of the measurements? Is there a future for ultracold atoms in tests of fundamental physics as general relativity? How far can one pursue the analogy between the Gross Pitaevskii equation used to describe BEC's and the nonlinear Schrödinger equation widely used in non linear (classical) optics?

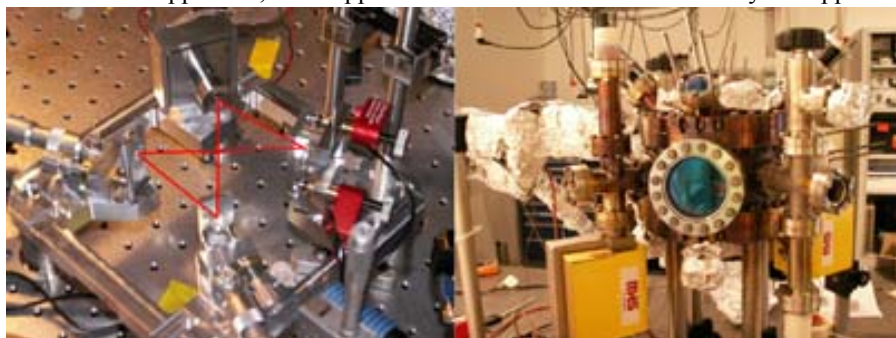
We will strive to address these problems using our various experimental set-ups developed or under development. We can present them in three main themes. The first one is about "Atomic interference, squeezing and entanglement". The second is about the interface between "Bose-Einstein condensates and condensed matter", mostly studies of degenerate fermions-bosons mixtures and localization phenomena. The third theme is about technological aspects of the development and use of inertial sensors and coherent atomic sources.

Atomic interference, squeezing and entanglement

The first set up allowing us to address this topic is our *guided atom laser* where we outcouple a quasicontinuous matterwave from a condensate to a horizontal atomic guide. One particular feature of this device is the ability to obtain wavelength comparable to optical wavelengths. With the help of various designs of optical potentials, we have a unique tool to study the propagation phenomena in a guide, including the effect of various obstacles (well, barrier, random potential, microcavity...). Such studies are extremely interesting from both theoretical and experimental sides. Understanding these phenomena is essential to master the guiding of matter-waves on microchips, with the goal of ultra-miniaturized atomic interferometers.

Among the various configurations that we envisage, we will first focus on a *double potential barrier which forms a Fabry-Perot cavity for the guided atom laser*. It will allow us to accurately characterize the spectral width of the laser, and may lead to an extremely "monochromatic" laser source. Moreover, we expect rich phenomena related to the non-linearity resulting from interactions between atoms. As with a Kerr medium placed inside an optical cavity, bistability should be observable, with only a few atoms. This effect is likely to profoundly change the density fluctuations of the transmitted laser. If we follow the analogy with light, such a system is able of squeezing the quantum fluctuations of light, and phenomenon of antibunching is predicted.

Another apparatus, developed thanks to a collaboration with Syrte supported by IFRAF, will allow us to investigate the

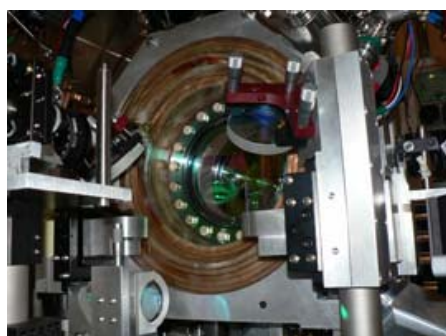


possibility to use *non-classical atomic sources* detection of phase shifts below the classic quantum projection noise limit. For this we are developing trapping and coherent manipulation of atoms using a high finesse cavity in a vacuum chamber (see photo). This cavity will provide «non-destructive» detection of atoms, and thereby squeezed atomic samples. Detection below the "standard quantum limit"

should be possible.

Bose-Einstein condensates and condensed matter

New possibilities are opened by the availability of high power lasers, and we have developed an apparatus to achieve



quantum degeneracy of bosons-fermions mixtures in an all optical atom trap. Potassium 40 (fermion isotope) and rubidium 87 (boson) atoms are trapped in crossed laser beams of 50 W at 1560 nm, and evaporative cooling leads to quantum degeneracy for the 2 species. A strong, homogeneous, magnetic field up to 1200 Gauss will be used to control interactions via Feshbach resonances. With controlled optical potentials, periodic or disordered, imposed onto the atoms, this apparatus will allow us to simulate condensed matter problems, with cold atoms replacing the electrons.

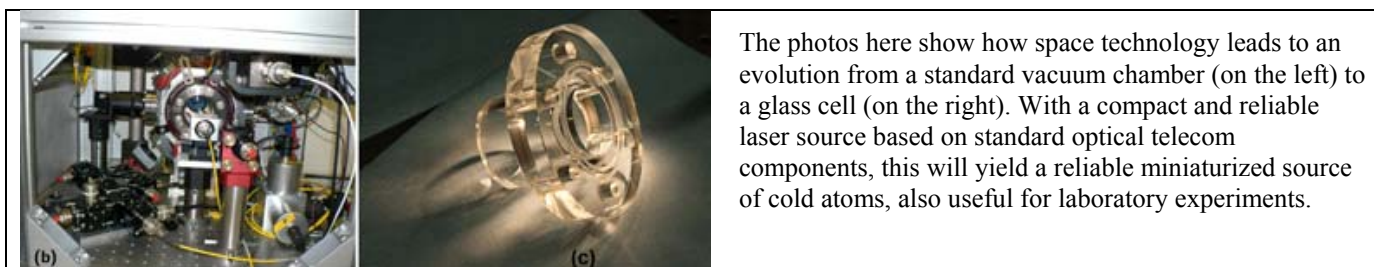
The first problem we intend to address is Anderson localization in 2 dimensions, with controlled interactions. Even the case of a non interacting gas raises still open theoretical questions. We plan to carry out such studies both for bosons and

fermions. When we have a quantum degenerate gas in the presence of disorder, we will also address the question of the rich phase diagram of a stationary sample, looking in particular for the celebrated Bose glass. Interesting results already obtained by our theory team will be an invaluable guide.

R&D in compact inertial sensors

Inertial sensors based on atom interferometry represent a potential breakthrough for future ultra-precise acceleration and rotation sensors, such as used in land, air and space navigation, geodesy. The exploitation of these sensors will be possible if we are able to simplify and miniaturize devices first developed in laboratories. This miniaturization demands fundamental investigations on the use of new sources of atoms for miniature sensors. We aim to strengthen the scientific know-how developed in our group, to gradually convert it to industrial know-how. Conversely, we expect that industrial developments will benefit to our basic research, by providing reliable pieces of equipment such as dedicated laser sources, or cold atom sources. These two developments are on our agenda. On the one hand, we will explore the possibilities of integration and hybridization of several optical architectures to design a compact laser source to manipulate atomic wave packets. On the other hand, through the construction of a prototype of miniature sensor, we will explore integration and hybridization of various optical and magnetic functions, possibly on an atom chip.

Space offers an exciting playground for cold atoms, and pioneering programs as PHARAO have demonstrated that it is a challenge that can be taken up. We intend to continue our efforts in this domain thanks to the ICE collaboration (Interférométrie Cohérente pour l'Espace) whose goal is to test the equivalence principle with cold atoms in microgravity available in the 0 g airbus plane. We will compare the behavior of potassium and rubidium, two elements with significantly different masses and nuclei composition, with atom interferometry methods. In the long term, the experiment could be upgraded to fly in a drag free satellite...



2.2.2 NANO-MANIPULATION AND QUANTUM ATOM OPTICS (C. WESTBROOK, D. BOIRON, I. BOUCHOLE)

Compared to optics with light, the field of atom optics, which has drawn significant inspiration from the former, is still in its infancy. Only about 15 years ago did the first research groups and conferences emerge with the name "atom optics". Still, intense experimental and theoretical activity throughout the world is producing rapid advances often borrowing ideas from photon optics. The 1990's saw the development of atom interferometers and the production of the analog to the laser: the Bose-Einstein condensate. The present decade has seen the beginnings of quantum atom optics, in which quantum fluctuation phenomena and entanglement play an important role. The observation of sub-Poissonian statistics⁴ and the realization of a two q-bit gate in an optical lattice are⁵ notable examples. The metastable helium experiment as well as the atom chip setups in our laboratory are well placed to play a role in this new field. Our measurements of atom correlations as discussed in the summary constitute our initial contribution to this field, and it seems that this is only a beginning.

A second, related new field is the exploration of non-trivial, highly correlated systems in many body physics. An example from our group is our study of one dimensional Bose gases: the behavior of both the density profile and of its fluctuations, even in the weakly interacting case, point to a regime in which interaction induced correlations between atoms render simple, Hartree-Fock-type treatments inadequate. Highly correlated systems have many close parallels in condensed matter physics and collaborations between workers in condensed matter physics and in quantum optics is beginning in many places including at the Institut d'Optique.

Another long term perspective of these projects is in the domain of quantum information processing, a field which is causing us to ask new questions about quantum mechanics. We already know that the manipulation of quantum bits constitutes a computing machine which is fundamentally different from a classical computer. Such a computer could tackle problems hitherto inaccessible, such as finding the ground state of a correlated N body system. But can such a computer actually be built and can we control its actions at the quantum level with sufficient accuracy? The answer must be in part experimental and some of the proposals below may help to answer the question. In the following paragraphs, we discuss some more specific lines of research for the metastable helium experiment and the atom chip program.

The microchannel plate (MCP), with its ability to count individual metastable helium atoms, can be viewed as the analog of the avalanche photodiode, one of the basic tools of experimental quantum optics. We have already begun to use the MCP to observe correlated atom pairs produced not by wave-function symmetry as in the Hanbury Brown Twiss effect, but by

⁴ G. Jo et al., arXiv:cond-mat/0608585.

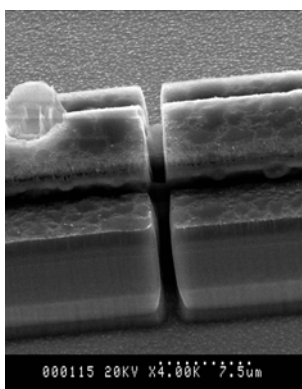
⁵ M. Anderlini et al., Nature 448, 452-456 (2007)

interactions – binary collisions between atoms in colliding condensates. This type of configuration should permit the realization of many analogs to the classic quantum optics experiments: The violation of Cauchy-Schwartz⁶ inequalities established for classical fields, the Hong Ou Mandel effect⁷ and possibly the violation of Bell's inequalities. Indeed, atoms created in binary collisions are entangled in position and momentum in the sense of Einstein Podolsky and Rosen. An important experimental challenge is to demonstrate this entanglement.

From the point of view of analogs to strongly correlated systems in condensed matter, the introduction of an optical lattice appears to us to be an important step in our research. Clearly, the presence of a periodic potential brings the a cold atom system much closer to typical condensed matter systems. The possibility of varying the tunnel coupling in such a lattice adds an important degree of flexibility. Hubbard models and phenomena such as quantum depletion, can be studied effectively in such a lattice. The study of quantum depletion, which should generate detectable atom pairs in momentum space, appears to be a particularly good place to start in looking for how metastable helium in a lattice can contribute to our knowledge if such systems. Finally, during the coming years, we plan to add the possibility of using metastable helium-3, a fermion, to our arsenal of experimental tools. The study of Fermi-Bose mixtures is still young, and the helium-3 helium-4 mixture is quite unexplored – Could there be Feshbach resonances in this system for example?

Atom chips also offer many possibilities to explore correlation and entanglement effects. A one dimensional Bose gas for example, at sufficiently low density can enter the strongly interacting, Tonks-Girardeau regime in which the particles become strongly anti-correlated because of their energy of interaction. The anti-correlation means that a gas of such bosons acquires the local properties of a gas of fermions. Our shot-noise limited imaging system, used in the study of the weakly interacting gas can, with improvements in the resolution, be adapted to the Tonks-Girardeau gas. Although we cannot expect to directly observe the pair correlation function, its characteristics will manifest themselves in the density fluctuations. We expect to observe sub-shot noise fluctuations when we enter the Tonks-Girardeau regime (Fluctuations in the number of atoms N in a small volume smaller than \sqrt{N} .) The same detection system can lend itself to the observation of density fluctuations in a two dimensional gas. In this case, interactions between the atoms drive the system to the a Berezinski-Kosterlitz- Thouless⁸ transition in which the proliferation of vortex-antivortex pairs play a key role. Strong density fluctuations should signal this type of transition and their study in the neighborhood of the transition is of great interest.

We have also recently begun a project, in collaboration with the Laboratoire de Photonique et Nanostructures to study a



new kind of atom chip. We aim to integrate an optical element (a Fabry-Perot cavity) on the chip. Our aim is to construct this cavity directly on the chip by microfabrication. We have already made single-mode ridge waveguides from GaAlAs and shown they are sufficiently transparent at 780 nm, the transition wavelength of Rb to make a cavity with a finesse of order 100. We plan to superpose by fabrication, such a cavity with the metallic wires which can guide atoms and thus have trapped atoms interact with guided photons. Such a system will permit even higher resolution imaging of a Tonks-Girardeau gas than what we mention above. In addition, the mode volume is sufficiently small that the hoped for finesse will put the cavity in or close to the strongly interacting limit in which quantum non-demolition measurements of atomic position are possible. Although other groups have also added optical cavities to chips, we are alone in attempting to create an entirely microfabricated system. If we succeed, we will be able to massively "scale up" the number of such cavities on a single chip, and the investigation of questions of quantum information processing can begin.

2.2.3 QUANTUM ATOMIC GASES – THEORY (*L. SANCHEZ-PALENCIA*)

Ultracold atomic systems have now reached an impressive degree of control as demonstrated in several recent experiments. Hence, realizing « quantum simulators » to solve complicated problems seems now within our grasp. For instance, the successful experiment on Anderson localization in the team of P. Bouyer (Nature, 2008) has recently renewed the field of disorder in ultracold atomic gases. It is our ambition to pursue our theoretical studies of quantum, disordered systems in strong collaboration with the experiments of the « groupe d'Optique Atomique » and to further develop long or mid-term prospective investigations.

Anderson localization in speckle potentials

Anderson localization of non-interacting one dimensional matterwaves can now be considered as demonstrated by textbook experiments. However, there are still open questions that can be addressed in the context of ultracold atoms. One interesting question is the effect of finite-range spatial correlations of the disorder on localization in 1D. Speckle potentials offer rich possibilities and in particular that of designing the spatial correlation function almost at will. We expect that exotic speckle potentials could lead to new situations where localization behaves counter-intuitively. We shall explore such situations

⁶ X. Zou, L. Wang, L. Mandel, Opt. Comm. 84, 351 (1991).

⁷ C. K. Hong, Z. Y. Ou, and L. Mandel, Phys. Rev. Lett. 59, 2044 (1987).

⁸ V. L. Berezinskii, Soviet Physics JETP, 34,610 (1971). J. M. Kosterlitz and D. J. Thouless, J. Phys. C: Solid State Physics, 6, 1181 (1973).

which can be expected to deepen our understanding of Anderson localization. Another important question concerns the manifestations of Anderson localization in dimensions 2 and 3 for which exact theoretical approaches are lacking. For instance, the scaling laws of the localization length are not known exactly and experimental data would help our understanding of localization. We shall analyze possibilities of ultracold atomic gases (bosons and/or fermions) to address this question and propose un-ambiguous experiments. For instance, we shall take into account possible anisotropies in the system. Anticipating exploitable experimental data, we shall participate to the physical interpretation and hopefully refine the picture of Anderson localization in dimensions 2 and 3.

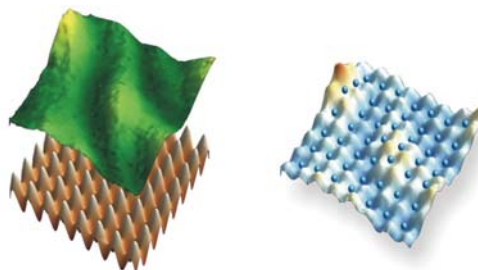
Interacting Bose and Fermi gases: Towards strongly correlated regimes

One of the most challenging questions in disordered systems is the that of the effect of inter-atomic interactions on Anderson localization. There are already many studies of this problem but they are still a bit puzzling. Indeed, the answer often strongly depends on the system (for instance, bosons or fermions, 1D, 2D or 3D, ...), on the regime (weak or strong interactions) and on the observable (dynamic or static). The original tools that have been introduced with ultracold atoms (eg direct imaging of expanding matter-waves) call for new studies with new view-points. We shall first consider the expansion of a Bose-Einstein condensate similarly as in the recent experiments and study the effect of weak interactions. Intuition may tell us that the localization length should increase with repulsive interactions. However, recent theoretical results on the transmission through a disordered region plead for the opposite answer ! Since a transmission experiment is different from an expansion, a careful investigation is required. Further, what does happen in 2D and 3D ? for attractive interactions ? for fermions ?

We shall also study strongly interacting systems. We shall further investigate the Lifshits glass regime by developing new theoretical approaches and extend these works to strongly correlated systems. One important goal would be to address the problem of Bose glasses which is still elusive. We shall aim at identifying un-ambiguous signatures of Bose glasses that are still lacking in the context of atomic gases.

Quantum magnetism in disordered ultracold gases: Mysteries in spin glasses

A longer term perspective is to further develop our investigations of disorder in classical or quantum systems where important questions remain open. One of the most stimulating ones is that of spin glasses. Spin glasses are Heisenberg-like magnetic systems where the exchange terms are randomly positive and negative. To date the phase diagram of spin glasses is not known and there are competitive theories. We plan to combine recently demonstrated possibilities to mimic spin systems with ultracold atoms with disorder to address this question.



Strongly correlated ultracold atoms in an optical lattice plus disorder (Figure adapted from White et al., arXiv:0807.0446).

2.2.4 STUDY OF THE PROTEIN TRANSLATION BY A SINGLE RIBOSOME (N. WESTBROOK, PH. BOUYER, K. PERRONET)

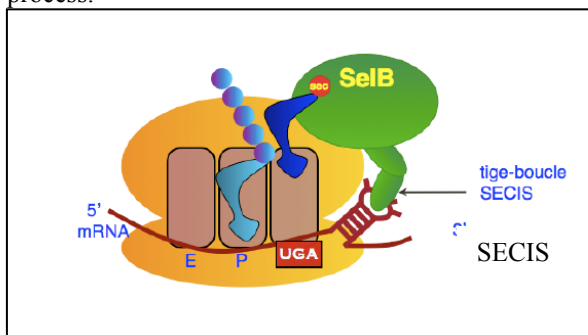
The heart of our project is to study the ribosome dynamics at the single molecule level. This extremely complicated molecular motor has been and still is studied by biologists who use their own tools, giving snapshots of frozen systems at a given step of the translation process, or average values coming from ensemble measurements.

The advantage of the tools we are developing, in particular single-molecule observation and manipulation, is to open the door to dynamics studies. Indeed, the number of articles concerning single-ribosome studies has increased very rapidly within the last 4 years, while we were starting our program. We are now in a position to contribute to this field. Our experimental setup allows us to combine fluorescence microscopy and optical tweezers. By that mean, we can simultaneously locate the different factors and measure the forces exerted by ribosome, and so, have a global vision of the translation process. As of today, only few groups have demonstrated the possibility to combine these two techniques, and nothing has been published yet on the ribosome combining both methods.

The work currently in progress concerns the kinetics of amino-acid incorporation in a growing protein by a single ribosome. We will push this project as far as possible, and we expect to obtain original results. With the success of this project, we will dispose of an active translation system fixed on a microscope slide. This points to further studies of the translation process by TIRFM alone or combined with optical tweezers.

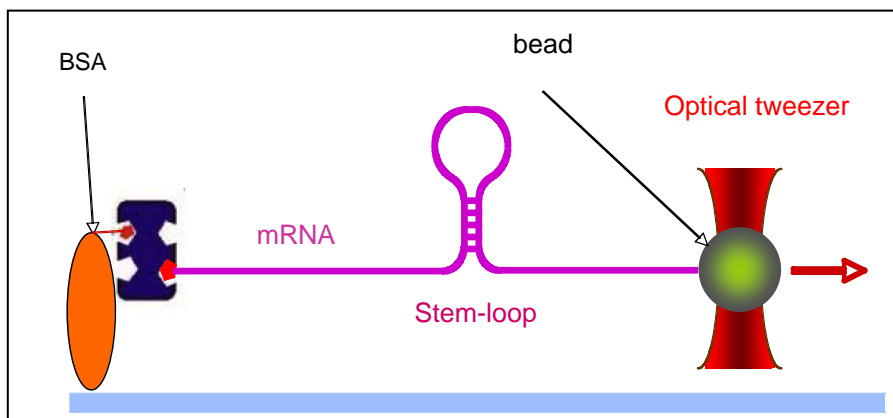
Out of all the interesting processes involved in protein synthesis, we are presently focusing on a specific step in the translation of a selenoprotein. Lack of selenium is involved in early aging, cardiovascular diseases and cancer. Its main biological form is selenocysteine, an amino acid which has no corresponding codon in the genetic code. In order to incorporate it in a protein, cell translation machinery uses dedicated tools, including a specific elongation factor (SelB) and a specific secondary structure on mRNA (SECIS for Selenocysteine Insertion Sequence) combined with a UGA codon (usually the stop

codon). Our project aims at studying the interactions between different factors (proteins, mRNA structures) involved in this translation process.



*Incorporation of a selenocysteine in a growing protein:
The usual elongation factor is replaced by SelB, able to recognize SECIS and thus making the ribosome interpret the UGA stop codon as a codon for selenocysteine.*

We will first use optical tweezers to measure the force necessary to open the SECIS structure. We will compare this force for SECIS isolated or interacting with SelB. This will help us understand how the ribosome melts this structure in order to move further on the mRNA while and after incorporating the selenocysteine. This project has attracted a new PhD student who will start in November 2008. We also hope to welcome Koen Visscher, assistant professor at University of Arizona in Tucson and a well-known specialist of optical tweezers for biology, as a long term invited professor.



*Schematics of the experiment:
The mRNA structure will be held between a microscope slide and a micron-sized bead trapped by a laser. The location of the bead in the trap – measured with a nanometric resolution – gives the force exerted by the laser on the RNA strand.*

A second step will be to get information on conformational changes between SECIS and SelB occurring during the opening of the structure, using resonant energy transfer (FRET) measurements. Our biologist collaborators have already solved the structure of the interacting domains of SelB and SECIS⁹. The combination of optical tweezers and FRET measurements will show the conformational changes occurring during the opening of SECIS by the tweezers.

⁹ Structural Insight into a Molecular Switch in Tandem Winged-helix Motifs from Elongation Factor SelB, N. Soler, D. Fourmy and S. Yoshizawa, Journal of Molecular Biology, 370, 728 (2007)
Page 19 – Atom Optics

CHAPTER 3 – FUTURE PROSPECTS OF THE QUANTUM OPTICS GROUP¹⁰

Head: GRANGIER Philippe

Directeur de Recherche

Faculty and Research Faculty holding permanent positions

BROWAEYS Antoine	Chargé de Recherche
TUALLE-BROURI Rosa	Maître de Conférences
MESSIN Gaétan	Maître de Conférences
SORTAIS Yvan	Maître de Conférences

Engineers, technicians holding permanent positions (seconded more than half time from the engineering support department)

FUCHS Florence	Ingénieur de recherche
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Doctoral students already present at the time of this writing and who are not expected to graduate before the end of 2009

FERREYROL Franck	C'NANO, 2007
FUHRMANEK Andreas	EDOM, 2008
EVELLIN Charles	DGA, 2008

¹⁰ See list of acronyms and explanations page 10

3.1. – INTRODUCTION

The domain of expertise of the Quantum Optics group is the experimental study of specifically quantum properties of light. This includes for instance single photon states and interferences, squeezed light, quantum non-demolition measurements, which have been extensively explored by our group in the 1980's and 90's.

Since 2000, our work has been focussing 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 states 0 and 1. Two main applications of QIPC are now actively studied worldwide, and as detailed in the report, our group is active in both:

- quantum key distribution, also known as quantum cryptography: the idea here is to establish secret communications by exchanging a "secret key", with a secrecy warranted by the laws of quantum physics;
- quantum computing: the idea is that 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.

Our activity is thus centered along the following lines, where we specify now the current level of support in funding and personnel:

(1) implementation of single photon sources using coloured centers in diamond. This activity is mostly done in collaboration with the group of Jean-François Roch at ENS Cachan, and it is presently supported by the ANR project « PROSPIQ ». It is therefore somehow sidelines with respect to the main research activities within LCFIO, and continuing it or not will be a question of seizing opportunities, and possibly of developing new collaborations.

(2) quantum optics and quantum cryptography with continuous variables. Our group has a recognized world-leading role in this activity, acknowledged by several international prizes (such as the QCMC award), a large number of invited conferences, two articles in "Nature", one in "Science", five in Phys. Rev. Lett., among which four "highly cited" papers. After 3 previous European projects, the contractual support remains quite good, since a new EC contract ("COMPAS", which is a "STREP" in ICT / FET) is starting in 2008. Support has also been granted by C'NANO and RTRA. However, three successive attempts to recruit a permanent CNRS researcher (with excellent candidates) have failed repeatedly, which can eventually compromise this whole research line. Presently the activity is taken in charge by Rosa Tualle-Brouri (MdC), who recently got her habilitation, and who is now seeking a professor position. It is unclear whether this change will allow her to continue working in our group. So a very firm support from *IO-GS* for some permanent positions is clearly needed here.

(3) manipulation of individual atoms in microscopic optical dipole traps (optical tweezers). This activity, quite successful also, is supported by the large frame EC Integrated Project SCALA, coordinated by Philippe Grangier, as well as by several other funding institutions (ANR, the US ARDA/DTO, IFRAF, Marie Curie actions...). In the group it is taken in charge by Antoine Browaeys (CR1), Gaétan Messin (MdC), and Yvan Sortais (MdC). Various EC calls are now open or will open soon, such as a new QIPC call expected at the end of 2008. Therefore the status of the work and support seems presently adequate, with very good prospects for the future.

In the following sections we give some precisions on possible developments for subjects (2) and (3) in next years. The goal is to shine some light in a few directions, and certainly not to give an exhaustive view of the future.

3.2. – QIPC WITH QUANTUM CONTINUOUS VARIABLES

3.2.1 QUANTUM CRYPTOGRAPHY WITH CONTINUOUS VARIABLES

After the end of the IP SECOQC (fall 2008), this activity will be pursued within the framework of the new (just starting) ANR project « SEQUIRE », in collaboration with Thales and ENST. It should be noticed that in the project we plan to develop a « hardened » version of QKD (quantum key distribution) box, which will be realized in close collaboration with our technological platform IOTECH, which is explicitly included in the project.

Longer term evolutions will be determined by future calls in FET / QIPC, but also in the EC Unit « Photonics », which has specific plans to support quantum communications projects. In particular, it is envisioned to submit new developments along the direction of SECOQC, in a new IP tentatively called « AQUA ».

3.2.2 GENERATION OF LIGHT FIELDS WITH NEGATIVE WIGNER FUNCTIONS

Here we present some details on the planned work on this subject, in correspondence with the STREP project « COMPAS » which is just starting with a duration of 3 years.

(i) Engineering non-Gaussian states of light

The objective of this task is to address the generation of highly non-Gaussian states of travelling light with negative Wigner function, in particular high-N Fock states and single- or multi-mode "cat states". As already explained, these states are essential elements for CV (continuous variables) quantum information processing. The role of measurement-induced

techniques will be established. This task, supplemented with the “breeding” of cat states, should pave the way to the demonstration of CV cat-states computing, in particular the C-NOT and Hadamard gates that will be realized.

(ii) Investigating measurement-induced CV information processes

The objective is to analyze the measurement-induced nonlinearity that may be attained by combining linear coupling, single-photon counting, homodyne detection, feedforward or conditioning. Such nonlinear operations are crucial to address universal CV quantum computation and CV entanglement purification. Several CV information protocols will be realized in order to demonstrate this paradigm, which will then be exploited for the realization of computing protocols. A toolbox for process tomography will also need to be developed for assessing the fidelity of the measurement-induced processes.

(iii) Investigating alternative schemes for photonic and/or atomic quantum gates

This task will explore novel effects that may potentially be exploited in order to get a very high nonlinear effect. In particular, we will investigate the cross-Kerr effect that arises in an Electromagnetically Induced Transparency-type interaction of light with an atomic system. It is anticipated that the strength of this nonlinear interaction may be orders of magnitude higher. Another research avenue that will be pursued consists in exploring the possibilities offered by atoms trapped in optical lattices. These lattices could be used to create specific photonic states, useful for CV information processing. Alternatively, the photons could be used to detect atomic states. This may be a clever way to perform highly non-Gaussian operations.

(iv) Demonstrating CV one-way computing and/or cat-state computing

The first objective of this task is the generation of optical CV cluster states, composed of several squeezed modes, on the way to the demonstration of measurement-based one-way computing (also investigated in the project for its theoretical aspects). A second research direction will focus on the experimental demonstration of quantum computing with cat states, including the realization of quantum gates (Hadamard and/or C-NOT gates) within the CV paradigm.

It is to be noticed that (iii) above may lead to a connection between our QCV and «trapped atoms» activities. These points will be studied by Gaétan Messin, who has already worked on both types of questions.

3.3. – MANIPULATIONS OF SINGLE ATOMS IN OPTICAL TWEEZERS

As written above, our single atom trap experiments are very flexible setups, which can lead to many possible explorations in quantum information but also simply in physics, e.g. in the context of optical Feshbach resonances, nano-condensates, quantum light sources, etc. It is impossible to speak about all these possibilities here, so as an example, we give more details on the possibility of realizing quantum gates with Rydberg states.

Within the current development of nanosciences, one of the most exciting potential applications of functional nano-objects is in quantum information processing. In particular, neutral atoms are an extremely promising candidate as the “substrate” for a scalable quantum computing architecture. Individual neutral atoms can be trapped and manipulated optically using optical tweezers, and their long-lived internal states are ideal for storing quantum information. Long coherence times and fast single-qubit operations have already been demonstrated, and techniques such as optical lattices allow arrays of thousands of addressable individual atoms to be created.

The outstanding challenge in the field of neutral atoms quantum information is to couple these individual atoms together to perform quantum gate operations. An attractive way to establish a “giant” coupling between two individually trapped neutral atoms is to use transient excitations to highly excited (Rydberg) states. Atoms in Rydberg states have wavefunctions 10 to 100 nm in size, and they interact strongly with each other over distances of several microns via dipole-dipole interactions. This strong coupling can be exploited as a communication mechanism between the atoms, able to create entanglement on a very fast timescale. Combined with established techniques to create arrays containing up to several thousand addressable single atoms, this could provide a route to a scalable quantum architecture, which remains a considerable challenge.

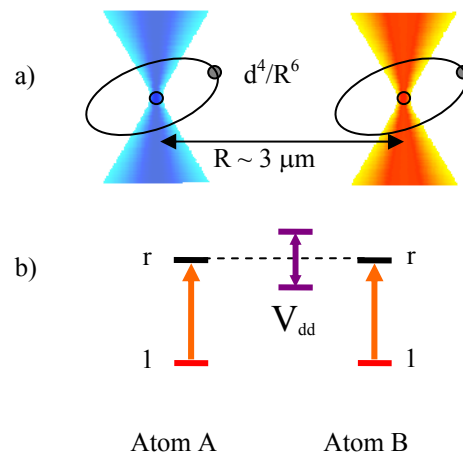


Figure 1: a) Observing the dipole blockade. Two atoms are trapped in individual optical tweezers a few micrometers apart and excited to the Rydberg state. b) Two atoms initially in the ground state 1 are simultaneously excited towards the Rydberg state r. Dipole-dipole interactions shift the doubly excited state rr out of resonance with the excitation laser.

Using the techniques that we have already developed, ground-state atoms can be cooled to temperatures $<10 \mu\text{K}$ and localized on the sub-micron scale using optical traps. At these low temperatures, the interactions between the Rydberg atoms dominate, and a Rydberg ensemble forms a novel many-body quantum system. Then it becomes possible to observe the dipole-dipole coupling between two rubidium atoms, individually trapped and manipulated in optical tweezers (see figure). This may allow us to exploit the dipole blockade (resulting from dipole-dipole coupling) as a communication / exchange mechanism for quantum information in arrays and ensembles of atoms, and thus to obtain entanglement and quantum gates between individual atomic qubits.

In addition, more on a physics side, the strong interactions between Rydberg atoms can give rise to new types of long range molecular states, with bond lengths of hundreds of nanometers. These include Rydberg/ground state dimers known as “trilobite” molecules (due to their exotic wavefunctions), as well as long range Rydberg-Rydberg states, known as « macrodimers ». So far, only indirect evidence of these bound states has been obtained experimentally.

Summarizing, the application of these innovative ideas about Rydberg systems in microtraps and lattices can potentially lead to many significant advances for quantum information, but also for quantum physics and for quantum nanosciences in general.

3.4. – TENDANCIES OF EVOLUTION

From a more general point of view, as it can be seen from the past history of our group, the evolutions of our research theme are very fast, and must be considered in an international framework. It is clear that Quantum Optics has opened a broad new field for scientific activity, leading to a more refined understanding of many processes in linear and non-linear optics. These ideas and techniques can flourish in relation with the current research on Quantum Information Processing and Communications, and will certainly keep developing in the years to come.

CHAPTER 4 – FUTURE PROSPECTS OF NANOPHOTONICS AND ELECTROMAGNETISM **GROUP (NAPHEL)¹¹**

Heads:

BENISTY Henri	professeur des universités
GREFFET Jean-Jacques	professeur des universités
LALANNE Philippe	directeur de recherche

Faculty and Research Faculty holding permanent positions

CAMBOURNAC Cyril	Chargé de Recherche
HUGONIN Jean Paul	Maitre de Conférences (Univ. Paris 6)
LAROCHE Marine	chargée de recherche
MARQUIER François	maître de conférences
SAUVAN Christophe	Chargé de Recherche

Engineers, technicians holding permanent positions (seconded more than half time from the engineering support department)

BESBES Mondher	Ingénieur de Recherche
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Doctoral students already present at the time of this writing and who not expected to graduate before the end of 2009

MAZOYER Simon	allocataire, 2008-
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Visiting scientists and post-doctoral fellows

WANG Bing	(Sep 2007 –)
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¹¹ See list of acronyms and explanations page 10

The research perspective of the Nanophotonics and Electromagnetism group covers three main topics: **photonic crystals, plasmonics, micro and nano-antennas**. Just as during the last four-year period, our activity will cover a variety of subjects under these main topics (nanocavities, slow light, emitting devices, novel plasmon effects, biophotonics ...). Our efforts will span the whole range including theoretical bases – with an aim at understanding the surprising properties of optical nanostructures unravelled by the present worldwide efforts –, more purpose-oriented modelling activities, and application-oriented projects that may lead to the validation of new devices with industrial partners.

With Jean-Jacques Greffet, François Marquier and Marine Laroche joining Institut d'Optique within the next few months, our group will be organised in three teams that gather strong complementary backgrounds and share a common interest in the above mentioned domain. It will be obvious in several cases that exchange of ideas between the three teams will be beneficial. We divide the presentation of our future works along the three above-mentioned scientific topics.

4.1 – PHOTONIC CRYSTAL CONCEPTS IN OPTOELECTRONICS AND IN ENERGY MANAGEMENT.

Photonic Crystals have gathered a large momentum in the last decade, fostering the general knowledge of periodic photonic systems in many respects. Waves in photonic crystals are heavily modified compared to continuous media, and in the simplest terms, dispersion is strongly affected. Some of the decade-old ideas, such as the super-prism could not be so tamed in a completely successful way, while, more recently, the so-called “slow light” structures have been the focus of much attention. Our group tackles this theme, which is quite demanding when it comes to designing genuine devices. We also deal with many other aspects of Photonic Crystals: the management of evanescent waves is made more versatile, since they are seen as spatial harmonics in the framework of photonic crystal. This opens many possibilities toward interaction with nanostructures, but more specifically for enhanced thermal coupling capabilities. It might also be that the interest of mesoscopic structures has so far been missed in the rush toward ultimate confinement. The existence of a sufficient fraction of modes undergoing extreme modulations could arise in mesoscopic structures that look like short multimode corrugated waveguides, but whose properties have been rather largely overlooked. Finally, materials are crucial to extend the applications of nano-structuring. Under that heading, ambitious work lies ahead at frontiers such as ultra-violet for bio-sensing or through the use of liquid crystals in photonic membranes toward controllable devices.

In many instances, the work is to be carried out with samples elaborated in the Thales – IO-GS – Ecole polytechnique common clean room facility, notably around the e-beam writer, which is now fully ready to fabricate sample devices. **This places a high expectation on the shoulders of younger technologically-oriented researchers, which would hopefully be backed by CNRS technical staff closely associated to the group in addition to the present support of B. Ea-Kim, who coordinates access to the clean room facility at the level of the whole laboratory rather than as a member of our group.**

Slow wave devices (P. Lalanne, C. Sauvan, J.P. Hugonin). Fabrication imperfections result in additional extrinsic losses as the group velocity is reduced. This is a crucial issue, since there is no point in exploring situations for which the reinforcement is immediately balanced by additional losses. To understand the impact of surface roughness and to design waveguide geometries with reduced sensitivity to imperfections, we will develop a theoretical framework that allows predicting losses in periodic waveguides. In addition, we will explore optical nonlinearities in Photonic Crystal waveguides. The latter basically show a small cross-sectional area on the micrometer scale and below. Including a slow light operation regime in the design should allow us to observe Raman laser oscillation in silicon chips (collaboration with the MANOLIA group). Current contracts: French ANR “MIRAMAN” (coordinator), SPLASH (FP7 STREP).

Thermal management, thermal radiation at micro and nano scale (J.-J. Greffet, M. Laroche). Heat transfer due to thermal radiation is dominated at nanoscale by evanescent waves. While this phenomenon could safely be neglected so far, it becomes important when dealing with nanoscale devices such as NEMS (nano electro mechanical systems). Other applications of heat transfer at nanoscale include heat-assisted magnetic recording and thermal management of electronic devices. We have two goals: i) to continue developing basic knowledge on these phenomena, ii) to develop models of the heat transfer accounting for nanoscale roughness and for dielectric layers. We shall also analyse the mechanisms involved for metals and dielectrics. This work has been started in collaboration with CEA-LETI within an ANR project.

Solar energy cropping (H. Benisty). the possibility to slow down light travelling in “Littrow modes” in broad corrugated waveguides may give rise to new possibilities to allow thinner and tinier pieces of photovoltaic material to be strategically interacting with the solar/luminous photon flux (e.g. as in tandem cells). Progresses are required for in-coupling, and for understanding the inner interaction with absorbers in such structures. This is indeed just the reverse of the goal of optimal extraction from nanostructured light sources.

Nonlinear and laser slow light structures (H. Benisty). The slowed down light of “Littrow modes” provides, more generally, a way to increase the light-matter interaction in favourable conditions, such as a less stringent mode matching requirements (multimode behaviour), or more robust resonators (if a resonator is monolithic, one replaces frail multilayer Fabry-Perot mirrors by gratings, e.g. robust Si or alumina gratings). This could be started in SoI structures for the linear part, and continued in GaAs or other structures in various collaborations (IEF, Lomonossov Univ., TRT), and/or in a FET Open Project. At the same time, basic research is needed to understand the demands on the grating and on the input/output systems to retain a large optical étendue. The latter feature would be the distinctive advantage of our approach over more confined ones, opening a niche between edge emitters and VCSELs-type geometries.

Photonic crystal Liquid Crystal controllable devices (C. Cambournac, M. Besbes). The capability to engineer silicon membranes can be further exploited by impregnating them with a liquid crystal, obviating the classical problem of the absence of tuning in blind holes. Fine modelling is needed for that task and has already been started. The inclusion of nanostructures in the liquid crystal could provide various interaction enhancement schemes with easy electrical/optical control.

Ultraviolet biosensing (H. Benisty). This is the continuation of the CIFRE thesis of K. Robin with TRT. A number of fundamental and practical issues are still to be clarified about the enhanced absorption detection at a grating surface. UV absorption allows label-free detection of DNA and proteins, and chips read with GaN-based 260-300 nm cameras could become very sensitive with carefully engineered substrates. The future stand open also on the possibility that biophotonics activity spinning off from the young company Genewave (Palaiseau), that was created with the participation of H. Benisty in 2001, receives academic attention in his team.

As a final possibility on the Photonic Crystal side, there is also a off spring of activity that we can foresee with IMEC after the success of our Sol (silicon on insulator) demultiplexing devices (CNRS patent filed as a result of our FP6 STREP FUNFOX), and possibilities arising from the EpixNet FP6 Network of Excellence, in which we have been affiliated.

4.2 – PLASMONICS

The emerging field of nano-photonics addresses the critical challenge of manipulating light on scales smaller than the wavelength of light. However, very few feasible practical approaches exist at present. Surface Plasmon polaritons are among the most promising candidates for subwavelength confinement, because energy can be stored in electron oscillations within dissipative metallic regions. Although promising, this interesting field faces many challenges that we are currently exploring.

Surface waves on metallic surfaces (P. Lalanne, J.P. Hugonin, J.-J. Greffet). Our recent findings on the existence and the property of the cylindrical wave (CW) at a nanostructured air-metal interface need to be further explored and we have several internal projects on the scattering of CWs and surface-plasmon-polaritons (SPPs) by nanostructures. Their aim is to understand the fundamentals of the electromagnetic properties of metallic surfaces textured at subwavelength scales. In addition to our present collaborators (Lionel Aigouy at ESPCI and Stéphane Collin at LPN), we are now taking new contacts who should allow us to explore various near-field situations from the visible to the THz spectral regions, and thus to discuss many aspects of the physics of textured metallic surfaces. We believe that understanding the properties of the waves scattered by subwavelength particles on metallic surfaces at a microscopic level is conceptually important for the domain. Also, we shall explore the fundamentals of imaging using surface plasmons. We shall develop the analogue of a Huygens-Fresnel principle for surface plasmons.

Quantum plasmonics (J.-J. Greffet, F. Marquier, P. Lalanne) A key challenge for surface plasmons and more generally surface waves is how to excite them and how to compensate their losses. Many groups are currently exploring the possibility to amplify surface plasmons. An electrically excited source of surface plasmons is the ultimate goal. Our first step will be to develop a formalism to quantize the surface plasmons and derive the stimulated and spontaneous emission rates. We will analyse quantum properties of surface plasmons (fluctuations, quantum correlations). We will explore schemes for exciting them electrically. This work will be carried out in collaboration with IEF and LPN in the ANR project LAPSUS. We shall also develop experiments to demonstrate the quantum nature of surface-plasmon-polaritons.

Negative-index metamaterials (new subject C. Sauvan, P. Lalanne). Metamaterials are artificially engineered structures that have properties not attainable with naturally occurring materials. Negative-index metamaterials (NIMs) offer new and unique properties for future applications like the emblematic superlensing and invisibility cloaking, but there could be also many other applications. NIMs were first demonstrated for microwave frequencies. At optical frequencies, they have so far been limited to optically thin samples because of significant fabrication challenges and strong energy dissipation in metals. In collaboration with Stéphane Collin at LPN and André de Lustrac at IEF, we have in mind to start an activity on the subject of NIMs at optical frequencies, with the objective to understand the physics there and to develop new approaches that are more realistic for applications.

There are two distinct aspects in NIMs: the realization of ultra-small low-Q resonators and the cascading of the resonators to form a mesh. Separately, the two aspects are fundamentals in nanophotonics. The interaction is responsible for the collective effective behaviour at large scales (band-structure). It is also important to realize all the potential impact of localized plasmon resonances for the reinforcement of light-matter interaction (see below the project on single photon sources, for instance). With NIMs, we are combining the two aspects to face a non-trivial regime of homogenization in the presence of local resonance. Our goal is to understand this regime, to develop approximate band structure models, and to study the absorption in narrowly localized resonances for increasing the figure of merit of NIMs at optical frequencies.

Imaging surface plasmons (JJ Greffet, F. Marquier, M. Laroche) The most widespread tool to observe surface plasmons so far has been standard microscopy where the fields scattered by residual roughness are imaged. The other choice is near-field microscopy. Recently, new techniques have been proposed: Photo-Emission Electron Microscopy (PEEM) and Electron Energy Loss Spectroscopy (EELS). We will collaborate with experimental groups (PEEM at CEA in the ANR project PEEM-Plasmon) to explore the potential of these new techniques. We will also collaborate with O. Stephan and M. Kociak to apply EELS to surface plasmons. Finally, we will explore how non-linear techniques such as frequency mixing can be used to excite and visualize surface plasmons.

4.3 – NANO AND MICRO-ANTENNAS

Nano-antennas and micro-antennas are becoming a central subject in nanophotonics. This concept embodies the design and fabrication of structures that enhance the interaction between light and matter. Applications include enhanced absorption for photovoltaic energy production and the design of single photon sources.

Fundamentals of nano-antennas (J.-J. Greffet, M. Laroche, F. Marquier). While the concept of nano-antenna has been introduced almost ten years ago and many theoretical and experimental works have been reported, there is still a lack of definition of the concept of impedance. Whereas the usual definition can be extended for antennas made of two wires, nano-antennas such as a tip or a metallic nano-particle that are currently being used to enhance and control the emission of a single emitter cannot be described in simple terms so far. This concept is fundamental to optimize the design of an antenna.

Single photon sources (P. Lalanne, C. Sauvan, J.-J. Greffet, F. Marquier). A common approach to modifying the emission properties of single emitters relies on microcavities in order to increase the Purcell factor. Yet, in many cases, the bandwidth needed is far larger than the micro-cavity bandwidth. We propose to take two different approaches to this problem. i) The first relies on the use of plasmonic nano-antennas, to control the Purcell factor and the quantum yield of the antenna. ii) The second approach is not based on the Purcell effect. Instead, we directly focus on the β -factor (defined as the fraction of the photons emitted into a single state to the total emission including the emission into radiation states).

1. The plasmonic antenna is essentially a patch antenna. This structure can also be viewed as a surface plasmon resonator. We will optimize the structure in order to enhance at the same time the Purcell factor, the quantum yield and the directivity. The potential of a strong coupling between the nano-antenna and the single emitter will be also examined.
2. We have recently predicted that quantum dots embedded into a Photonic Crystal waveguide can offer high β -values without any cavity (Purcell) effect. As a consequence, broadband (40 nm @ $\lambda=950$ nm) and efficient ($\beta>90\%$) photon funnelling may be achieved in a single mode. This theoretical work has been nicely verified experimentally by researchers in Forchel's group in Würzburg, who have derived from photoluminescence measurements that β -factors of up to 0.89 can be observed over as large a bandwidth as 20 nm, see arXiv:0805.3485v2 [quant-ph] (2008). We believe that this non-resonant approach needs to be further explored. In this spirit, we shall explore two routes that mix metals and semiconductors: the first construct is based on the emission properties of semiconductor nanowires with metallic mirrors (Collaboration J.-M. Gérard at CEA) and the second relies on ultra-small metallo-dielectric (Au/GaAs/AlOx) nanocavities with low-Q resonance (Collaboration I. Robert and I. Sagnes at LPN, within the NanoEPR project of the 2006 ANR and EU supported NanoSci-ERA programme).

Enhancing the efficiency of detectors for photovoltaics (M. Laroche, J.-J. Greffet). One of the major challenges of solar energy is to improve the efficiency of the photovoltaic cells. The main cause of efficiency reduction is the fact that IR photons below the band gap are not absorbed, while the UV photons energy in excess of the band gap is lost. Many advanced concepts have been proposed to solve these issues. They include up-conversion processes and hot electrons cells. Up-conversion suffers from a very low efficiency so that it is necessary to enhance the absorption. Similarly, hot electron cells must use extremely thin solar cells, so that absorption is significantly reduced. In both cases, absorption can be enhanced by using properly designed micro or nanostructures acting as optical antennas. Our goal is to design structures that can allow to absorb over 50 % of incident solar light with cells thinner than 100 nm. The major challenge is to design resonant structures with a large bandwidth. This study is done by a consortium lead by IRDEP (CNRS-EDF), supported by two ANR projects.

Daylight illumination applications (P. Lalanne, M. Besbes). Thanks to our expertise in electromagnetic modelling, we have intensified a collaboration with Saint-Gobain Recherche (one patent has been filed followed by the fabrication of a diffractive device using a nano-texturation at a multiwafer scale, a new contract has been signed in the summer of 2008, and other projects are under discussion). The opportunities given by Saint Gobain on "daylighting" applications appear really interesting since they combine applied research with precise objectives and long term visions on scientifically attractive subjects. We cannot afford to miss it – which means that we need to the scientific manpower to address the issue.

CHAPTER 5 – FUTURE PROSPECTS OF THE NONLINEAR MATERIALS AND APPLICATIONS **GROUP (MANOLIA)¹²**

Head: PAULIAT Gilles, directeur de recherche

Faculty and Research Faculty holding permanent positions

DELAYE Philippe	Chargé de Recherche
ARNAUD Carole	Chargée de Recherche
FREY Robert	Directeur de Recherche
CUNIOT-PONSARD Mireille	Chargée de Recherche
DUBREUIL Nicolas	Maître de Conférences
LEBRUN Sylvie	Maître de Conférences
JONATHAN Jean-Michel	Professeur des universités

Doctoral students already present at the time of this writing and who not expected to graduate before the end of 2009

BARON Alexandre	allocataire, since 2007
CONTRERAS Kevin	fellowship on international programme with Peru, since 2007

¹² See list of acronyms and explanations page 10

5-1. INTRODUCTION

As reflected by the name of our group, our originality and specificity are to gather the skills relative to the full chain ranging from the non linear materials, the physics of the optical non-linearities to the demonstration and development of functions and devices. For the period to come we wish to continue to concentrate our work on light/matter interactions in micro-and nanostructured materials. We thus have decided to cease some of our activities that are on the boundary of this main research axis such as the work on “self-organized laser cavities” which will stop at the end of the current European Brighter project (2010) and for which most of the investigations have now been completed. As we did in the past, we will remain attentive to the requests from the industry and from academic colleagues to be able to advise them and continue, as far as possible, to transfer our know-how.

For sake of clarity, we have split our anticipated work in several projects relative to the materials, devices and more fundamental physics. However, it is obvious that all these topics are strongly connected and feed from each other. On each of the following projects, beside the permanent staff, we want to train at least one PhD student.

5-2. PROJECTS

5.2.1 INVESTIGATION OF NEW ORIGINAL MATERIALS

We focus our studies on two classes of materials, which are not, or very poorly, studied elsewhere, which are within the scope of our thematic and for which we anticipate interesting physics and innovative applications.

a) Photo-induced phase transition in nanoparticles (Leader: Carole Arnaud)

There is nowadays considerable activity around the molecular switching materials, such as spin transition compounds and molecular charge transfer complexes. This activity is fed by the scientific interest in these not yet fully understood phenomena, and also by their numerous potential applications in the field of data storage, displays, or nano-actuators ... Scientific communities, such as the COMES GdR, recently renamed MCM, are well established. However they mainly consist of solid-state physicists and chemists, but nearly no one from the optical community even though there exist many potential applications in that area. We have thus decided to fill this gap and first to bring our efforts in a better understanding of the physical mechanisms. Because most studies have been conducted on powders or on macroscopic crystals we study microscopic and sub-microscopic objects, the size of which are closer to the size of the domains of the material. This should give a physical insight that complements studies conducted on powders. We will continue to use our DIC microscope to follow the hysteresis loop of individual spin transition nano-particles, and adapt it to measuring their photo-switching dynamics. This microscope determines the product “volume x refractive index” of the particle. In parallel, with our AFM microscope we will measure the change of volume during the phase transition. These studies will be conducted in strong interaction with our colleagues from ICMCB (Institut de Chimie de la Matière Condensée de Bordeaux), CPMOH (Centre de Physique Moléculaire Optique et Hertzienne, Bordeaux) and GEMaC (Groupe d’Etudes de la Matière Condensée, Versailles). We are already in contact with ICMMO (Institut de Chimie Moléculaire et Macro-moléculaire d’Orsay) to investigate other photo-switching materials (based on the LD-LISC effect, Ligand-Driven Light-Induced Spin Change), that could be better adapted to some specific applications.

We are first going to investigate the use of these switching materials for data storage. This study should be conducted in the frame of a MEDEA (cf <http://www.medeaplus.org/>) project called TRITON led by Philips and in which we will more specifically interact with ICMCB, CPMOH, and CEA/LETI. In a second step we also intend to develop new applications for these materials. For instance combining their “switching properties” to the photonic crystals we study in the group should lead to devices whose functionalities or characteristics could be wavelength tuned.

b) Hetero-epitaxial $Sr_xBa_{1-x}Nb_2O_6$ (SBN:x) thin films (Leader: Mireille Cuniot-Ponsard)

Until now we have focused on the Pockels effect and on a material which presents exceptional Pockels properties: $Sr_xBa_{1-x}Nb_2O_6$ (SBN:x). We succeeded in preparing epitaxial SBN thin films on conductive substrates. Our primary, and achieved, objectives were the experimental demonstration and quantitative analysis of electro-optical effects.

We developed a method to determine the electro-optical coefficients independently, without neglecting the other potential effects of the electric field (piezoelectricity, electro-absorption). Its implementation encounters difficulties when the interfaces roughness is significant, or when the parameters of the film (thickness, starting index) are poorly known. Developments are planned concerning the digital simulation and modelling implied in the data processing. The objective is to push the reliability and the precision of this method of determination of the electro-optical coefficients to its limit. Thanks to this method we wish to explore the couplings between the various effects of the electric field (electro-optics, electro-absorption, and piezoelectricity), the behaviour of these effects versus frequency, the relation between epitaxial strain and electro-optical properties, as well as between the strong dielectric non-linearity observed in the low frequency range and the non-linearity at the optical frequencies.

Another objective is to optimize the electro-optical properties of SBN films. Properties of SBN crystals are known to intensify with increasing Sr content in the solid solution, an exaltation effect related to the fact that the Curie temperature approaches ambient. In crystals, the electro-optical coefficient r_{33} is multiplied by 3 when the Sr content increases from 60 to 75%. A compromise is nevertheless to be found between stability and amplitude of the electro-optical coefficient. Our previous results have been obtained with a composition of 60% Sr. The best compromise between stability and electro-optical properties in films will be achieved by exploring higher Sr contents. The electro-optical properties already measured on our SBN films justify the attempt to structure them in the form of a functional guide. A first work will be devoted to the essential control of the films roughness, either through conditions of growth, or by polishing the film (already tested by us successfully). The structuring of films in the form of guides will be the object of a collaboration with a laboratory qualified in this field. An optical bench will be settled in the laboratory to test the propagation properties of these guides.

The dielectric non-linearity of our SBN films, at frequency <10 MHz, is comparable to that of the material extensively studied in the literature for its tunability properties: (Ba, Sr) TiO_3 . These properties, however, are of particular interest in the microwave field. They will be evaluated in this frequency range through collaboration with specialists in HF measurements (University of Brest or University of Calais).

With our local probe microscope, we can carry out cartographies of piezo-response and electrostatic charge (EFM), versus an adjustable temperature of (-30 to +200°C). We thus have performed the polarization “writing-reading” of a SBN film at a nanometric scale. In addition to giving access to the full information about film and electrodes topography, this tool allows to polarize and observe the induced effects at a nanometric scale, to study at this scale the approach of the Curie temperature or the frequency response. It is a vast field of physical studies, which we will explore. Mastering this domain reversal is also a key for our studies described in § 5.2.3 (d).

5.2.2 DEMONSTRATION OF FUNCTIONS AND DEVICES

The two following topics are motivated by the applications. Their originality derives from the knowledge we previously acquired. We still intend to feed them by the more fundamental studies we are conducted.

a) Very high capacity optical memories (Leader: Gilles Pauliat)

At the latest international symposia on optical data storage, more than 30 % of the communications dealt with holographic storage. The feasibility of this storage has been proven long ago and explains the marketing of a holographic disk player by InPhase Inc. Nevertheless, that technology as well as most of its competitors, using optics (near field storage, multilayer 2-photon storage etc.) address the archival market. Indeed, low cost mass replication of contents (as achieved with CDs and DVDs), which is the key to address the public market, is hardly achievable with these technologies and has not yet been demonstrated. According to the major stakeholders, holographic systems should be available in about 10 years. This leaves us enough time to conduct original research. Indeed, the page-oriented Lippmann data storage architecture we started to investigate during the last 4-year period is in principle compatible with mass replication: the analytical modelling we have developed proves that a “master” disk recorded by the Lippmann process can be replicated by contact and “white” light illumination. Our proposed approach thus looks very attractive provided our predictions can be validated. In a first step, we are thus going to demonstrate the page-oriented Lippmann architecture, using only 2 or 3 wavelengths, but with a pixel resolution of about 1 μm . This set-up is part of a PhD thesis started in November 2007. In parallel, we wish to demonstrate the replication of the data from one medium to another one.

Although the first demonstration can be conducted at the laboratory level, our full research programme only makes sense if we are able to establish strong collaboration with other academic and industrial partners. We already approached some partners, for instance in the discussions of the TRITON project (see §5.2.1 (a)). As soon as the first experimental demonstration produces results, we will reinforce these contacts.

b) Raman wavelength converters in microstructured fibres (Leader: Sylvie Lebrun)

We shall keep investigating stimulated Raman scattering in liquid core micro-structured fibres by testing new liquids in order to demonstrate the control of the Raman emission by playing on the transmission bandwidth. One goal is to force the emission on either the main Raman line, or on the secondary line by eliminating the main line. This doubles the number of accessible lines and thus the number of generated wavelengths. Besides we shall test new fibre structures to improve our understanding of the interaction between the non-linearity and the structuring. Our final goal is to optimize the structures to improve the quality of the generated beams and the efficiency of the conversion in order to realize efficient Raman conversions in the continuous regime. These Raman converters are of special interest for biology in which specific wavelengths are required to selectively excite fluorophores. Indeed, today’s available lasers do not easily cover the whole range of required wavelengths. We decided to investigate the realization of such a Raman converter. We have already contacted industrial and academic partners and have defined a “roadmap” to create an integrated system made of a unique pump laser (pulsed or continuous) on which several modules made each of a coiled liquid-filled photonic crystal fibre could be connectorized. This programme will start in the fall of 2008 with the arrival of a post-doc researcher.

5.2.3 INVESTIGATION OF OPTICAL NON-LINEARITIES IN STRUCTURED MATERIALS

With material structuring we can confine light and create optical resonances, which strongly enhance light-matter interaction. All our physical studies are aimed to a better understanding of this enhancement, determining the involved optical non-linearities and the interaction between them.

a) Parametric generation in microstructured fibres (Leader: Philippe Delaye)

Beside the Raman effect, we also study parametric generation in liquid filled or gas filled micro-structured fibres. Four wave mixing parametric generation allows tuneable amplification and generation easily controlled by the pump wavelength or fibre dispersion. It opens the way to the generation of new wavelengths not accessible with usual Raman liquids especially for the generation of photons at lower wavelengths than the pump. The photon generated by the parametric four wave mixing mechanism being created by pairs that opens the way to the realization of fibered generators of correlated photons for quantum communications systems. Due to the small Raman linewidth of the liquid and gases the simultaneously generated uncorrelated Raman photons, that usually degrade the quantum quality of the correlated photons generated in silica fibres, will be efficiently filtered. We already started to work to demonstrate and investigate these features by studying an acetone filled fibre for estimating its performances as a source for correlated photons.

b) Non linear optics in the evanescent field of nano-fibres (Leader: Sylvie Lebrun)

Our policy to develop miniaturized optical circuitry leads us to start a line of research on nano-fibres. These fibres are made of silica or of strongly non-linear materials with a diameter lower than 1 μm . Some studies were already published using the non-linear optical properties of the silica or the glass composing the nano-fibre, for example to generate of a supercontinuum. In association with the nanophotonic Group of the Dept. of Optical Engineering of the Chinese university of Zhejiang, we propose a radically different approach. When the diameter of the nano-fibre becomes of the order of some hundreds of nm, the evanescent field of the mode becomes very intense outside the fibre. By plunging the fibre into a strongly non linear liquid, the power density of this evanescent field should induce non linear optical effects in the liquid. This innovative approach offers a vast choice of non linear materials. It also allows to simply test new architectures: non linear micro-loops, coupled resonators ... We will begin by studying stimulated Raman scattering in liquids such as ethanol or benzene. Several geometries can be realized with these nano-fibres. At first we shall focus on simple geometries such as a straight nano-fibre and a resonator in micro-loop of a typical diameter of the order of some hundreds of micrometers.

c) Photonic crystal structures for data processing (Leader: Nicolas Dubreuil)

It is an objective of major importance to make best use of the maturity of the semiconductor technology for implementing photonic crystal devices. Efficient active resonant devices should be able to enhance the non linear interactions and thus significantly decrease the optical command powers. Nevertheless, an optical non linear interaction never comes alone and a complete mastering of all non-linearities and their modification by the material structuring is mandatory. Our strategy follows from this observation. We are thus working in two parallel roads:

1) *Understanding and enhancing the Raman amplification and electronic Kerr non-linearities.* In the frame of the MIRAMAN ANR project, pump-probe experiments will be conducted in SOI waveguides. Specific attention will be drawn on the influence of the material structuring on the life-time of the free carriers created by 2-photon absorption, on the refractive index change, and on the increase of the Raman gain. At the end of this project (Oct. 2010), the road to the implementation of a low threshold slow-mode Raman laser should have been opened. In parallel, similar studies will be pursued on the AlGaAs cavity with the aim of evidencing the enhancement of the Raman gain induced by the simultaneous pump and Stokes resonances. In collaboration with Thales TRT, we will also tailor the band gap in III-V compounds to design low loss waveguides and thus to benefit from pure electronic Kerr effect.

2) *Design and test of first non linear model devices.* We propose an original structure made of two coupled cavities working in electronic Kerr regime in order to implement an optical delay line with an optical control of the delay. This system will be developed through a PhD work in collaboration with Thales TRT. The device will be manufactured on the IO-TRT technology platform.

d) Nanostructured ferroelectric films for non linear optics (Leader: Philippe Delaye)

Second order non-linearities are more complex to investigate than the third order non-linearities we already investigated because there is no automatic phase matching. As proposed a long time ago already, photonic crystals could help implement this phase matching. One possibility consists in structuring the non linear coefficient, generalizing in 2D the 1D periodic polarization made in ferroelectrics (PPLN structures among others). Another possibility is to use the strong dispersion in the crystal band edge to phase match the waves. In the first case, we structure the second order non linear susceptibility whereas, in the second case, we structure the linear susceptibility. The latter technique allows very compact structures because besides allowing the phase matching, the operation in the band edge also insures the light localization, which enhances the non-linearity contrary to PPLN structures. However, light localization and phase matching must be simultaneously realized with the only structuring of the material refractive index, and that may turn out to be difficult if not impossible. To overcome this problem, we propose to independently structure the linear and non linear susceptibilities: structuring the linear susceptibility

would allow optimizing light localization, and structuring the second order non linearity would allow to optimize the phase matching. Cascade such second order nonlinear devices would open a way to mimic third order non linear functions. Entirely new devices will become feasible. For instance parametric generation with counter-propagating signal and idler wave should become a reality for implementing correlated photon sources with a very narrow line. We will start our work with theoretical studies to define simple structures in order to experimentally validate the concept. For these first experiments, we are going to use GaAs or GaN compounds, or LiNbO₃. They indeed present a strong second order non-linearity and the technologies for engraving and for domain reversal are already mastered by some groups. In a second phase, our aim is to adapt this double structuring concept to more promising materials, especially to the SBN thin films grown in our own group and in which we start to control domain reversal (§ 2.1.2).

CHAPTER 6 – FUTURE PROSPECTS OF THE LASERS AND BIOPHOTONIC GROUP (LASBIO)¹³

Head: Patrick GEORGES, directeur de recherche

The group consists of two teams:

“Solid State Lasers and Applications team” (ELSA) Head: Patrick GEORGES

“Matériaux, Composants et Systèmes pour la Biophotonique” (MaCSyBio) Head: Michael CANVA, directeur de recherche

Faculty and Research Faculty holding permanent positions:

ELSA		MaCSyBio	
BALEMBOIS François	Professeur des universités	MOREAU Julien	maître de conférences
DRUON Frédéric	Chargé de Recherche		
DUBOIS Arnaud	Professeur des universités		
HANNA Marc	Chargé de Recherche		
LUCAS-LECLIN Gaëlle	Maître de Conférences		

Doctoral students already present at the time of this writing and who not expected to graduate before the end of 2009

ELSA

Franck MORIN	BDI CNRS/Amplitude since 2007
Mathieu PAURISSE	Bourse DGA since 2007
Déline SACCHET	allocataire + monitorat since 2007
Igor MARTIAL	CIFRE Fibercryst, since 2008
Clara Saraceno	CIFRE Teem Photonics, since 2008
Viviane Devauges	allocataire, part time, with Laboratoire de Photophysique Moléculaire, since 2008
Guillaume Bloom	CIFRE TRT, since 2008

MaCSyBio

Mohammed NAKKACH	assistant à l'université de Tunis, co-tutelle, since October 2006
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¹³ See list of acronyms and explanations page 10

6.1 – SOLID STATE LASERS AND APPLICATIONS (ELSA TEAM) PROSPECT

During the next years, the research activities of the ELSA team will continue on the development on new diode-pumped solid-state lasers and their applications. Our aim is to benefit from our strong understanding of the laser physics to study new lasers architectures (based on different gain media: crystals, fibers and semiconductors structures) operating in different time/wavelength domains. Most of the time, these laser developments will be triggered by applications, especially in Biophotonics (fluorescence lifetime microscopy, high spatial resolution imaging, corneal and glaucoma surgery, cancer detection) but also in metrology (atomic frequency standards) and physics (high harmonic generation).

In the following pages, we describe our prospects in four research areas, following the structure of the research activity report. Biophotonic applications are treated as an additional subsection, and the section concludes with considerations on funding and personnel.

HIGH POWER DIODE PUMPED SOLID STATE AND FIBER LASERS

The optical power emitted by semiconductor laser diodes is continuously increasing, and high power solid-state or fiber lasers operating in the multikilowatt level are commercially available in CW (continuous wave) regime. However, the situation is more complex in pulsed regime, especially with rare earth-doped fiber amplifiers, since non-linear effects accumulate along the propagation in the small core and strongly limit the performance in terms of energy and peak power. Combining high average power and high peak power with a perfect diffraction limited beam remains a challenge and the subject of a hard international competition. Two ways of research are under progress in our laboratory and need large investigations in laser physics before emerging as mature solutions: the development of crystal fibers, and the study of multimode/multicore fiber amplifiers with active or passive laser beam management.

The concept of crystal fibers, combining the advantages of bulk crystals and fiber has proven to be a very promising concept, bridging the gap between crystals and fibers. Preliminary results with Nd:YAG and Yb:YAG samples show that a significant breakthrough in terms of performance (nanosecond to femtosecond pulses with mJ energy and with average power reaching tens of watt) can be achieved. The existing collaboration with the Laboratoire de Photochimie des Matériaux Luminescents of the University of Lyon and the French company Fibercryst will strengthen as crystal fibers reveal their potential and begin to be very attractive. With our colleagues, we will firstly concentrate on the elaboration of the medium itself with the required functionalities to increase the efficiency (optimization of the optical quality, elaboration of an optical cladding), and to limit the temperature increase (axial gradient of concentration, configuration optimizing the heat transfer coefficient with the mount). We will secondly investigate laser emissions never demonstrated with this kind of medium: 946 nm with Nd:doped and 1600 nm with Er:doped crystals fibers. We will also study the possibility to realize a directly diode-pumped Ti:sapphire crystal fiber laser taking benefit of the long absorption length of these devices; this would be to a breakthrough in the laser field. Thirdly, we will explore the potential of crystal fibers as pulses amplifiers. Preliminary studies demonstrate that crystal fiber amplifiers can combine both high small signal gain and high-energy extraction better than any other amplifier. A patent with Fibercryst is currently in preparation concerning a new configuration of pulse amplifiers. Finally we will try to explore the upper limit in terms of pump power, which should be located between 1 and 10 kW of launched power.

The main limitation of fiber amplifiers operating in pulsed regime being the accumulation of non-linear effects in the small core, we have been working for many years in close collaboration with TRT on several ways to overcome these limitations. We are currently studying the possibilities to control the output emission of a multimode large core diameter fiber amplifier by using a spatial light modulator (SLM) to shape the amplitude and the phase of the input signal in order to obtain a diffraction-limited amplified beam. Another way that we pursue is to use either a multicore fiber amplifier or several individual single mode amplifiers. After amplification, one has to control the relative phase from each core/amplifier to coherently combine the outputs. Different techniques based on SLM or numerical holography will be studied to achieve coherent combining. We are expecting significant results in the next few years on these topics and we will study the possibility to apply these techniques to short pulse fiber amplifiers.

DIODE-PUMPED SOLID-STATE VISIBLE AND UV LASERS

All solid-state diode pumped visible lasers are being developed to replace gas lasers for many applications, mainly in biophotonics. Two years ago, the ELSA team has started a collaboration with the French company Oxixus that is manufacturing visible single frequency microchip lasers. We have recently demonstrated the potential of the intracavity pumping concept to reach new wavelengths in the visible. This concept can be applied to a wealth of configurations and open new ways of pumping that have never been studied. Hence new laser architectures (such as three photon absorption) will be investigated to reach the blue wavelength band (490 nm) in order to replace argon ion lasers. Moreover, we will work on laser media emitting directly in the visible and pumped by recently developed high power GaN blue diodes.

A new research project, funded by the CNano program, will concern the development of a solid-state laser operating at 465 nm in order to excite Eu doped YVO₄ nanoparticles for fluorescence bio-sensors. Two approaches will be investigated: either the sum frequency mixing between two lasers lines of Nd:YVO₄ (914 nm) and Nd:YAG (946 nm), or the frequency doubling of the 930 nm line of the Nd:YAP crystal. This work will be done in collaboration with the Laboratoire d'Optique et

Biosciences and the Laboratoire de Physique de la Matière Condensée from the Ecole Polytechnique, Palaiseau. It should be noted that, if the prototype reaches good performance, Oxxius is interested in commercializing such a laser, since a potential market for these applications has been clearly identified.

The pulsed sources developed with crystal fibers will have unique performance in terms of peak power and average power. It will hence be possible to easily reach the UV band (200-300 nm) by non-linear frequency conversion providing new laser sources that can compete with existing excimer lasers. However, one key point is the non-linear crystal. Nowadays, only LBO, BBO and CLBO non-linear crystals are commercially available, but with non-optimized properties (residual absorption band) preventing the operation at high average power. In collaboration with Ecole Nationale Supérieure de Chimie de Paris and the two French companies Cristal Laser and Eolite, we are studying the properties of new non-linear crystals of the Borate family. Our contribution will be firstly to develop a new set-up for phase matching evaluation based on a pulsed white light source and secondly, in the longer term, to test these new crystals with high average power sources.

EXTERNAL-CAVITY SEMICONDUCTOR LASER SOURCES

Our work on semiconductor laser sources will be the continuation of the two topics already started since a few years, taking advantage of our successful collaborations with either growth laboratories (LPN and the Alcatel-Thales - III-V Lab) or our background in these fields. Our aim is to make best use of the good properties of semiconductor materials and structures (high efficiency and large spectral coverage) to investigate new laser architectures.

Following our work on 852-nm single-frequency Vertical Extended Cavity Surface Emitting Laser (VECSEL), we intend to take further advantage of our expertise gained in the last years on the growth and design of active semiconductor structures at this wavelength within our close collaboration with the LPN and the Institut d'Electronique du Sud. The increase of the output power under single-frequency operation will be investigated with the aim to extend the potential of these laser sources for inertial sensors, within a project partly funded by the Laboratoire National d'Essai (LNE). Two different approaches are being considered: on the one hand, we will try to improve the thermal behaviour of the device, which will require further technical developments on the component itself; on the other hand we could test ultra-short cavity designs that could allow to obtain a high-power (> 200 mW) single-frequency emission without lossy intracavity spectral filter.

Furthermore, we will theoretically and experimentally investigate the two-frequency/two-polarization operation of an optically-pumped VECSEL within a collaboration with TRT and the Observatoire de Paris. Such a source could be an alternative to the two independent phase-locked lasers that are currently used in CPT (Coherent Population Trapping) atomic clocks. We will take benefit of the knowledge of TRT on two-frequency solid-state lasers. This work, which will allow us to investigate the VECSEL physics thoroughly, would take benefit of many different features of these sources.

Finally, we expect to be able to extend the spectral range of single-frequency VECSELs for other applications, by changing the semiconductor structure or by non-linear frequency conversion.

Concerning the improvement of the spatial and spectral properties of extended-cavity diode laser bars, we intend to apply to infrared quantum cascade lasers (emitting around 4 μm) the different techniques that we have already implemented in the near infrared; both the spectral and coherent combining of emitters will be investigated, with the aim to increase the brightness of these sources. This work will be undertaken in collaboration with TRT.

ULTRAFast LASERS

Our specificity in the diode-pumped ultrafast laser-system area is to investigate innovative materials, architectures, and physical effects able to generate and amplify extremely short pulses (<100 fs). Building on this expertise, we will in the next few years concentrate our research on the physics of ultrafast laser sources that allow simultaneously the generation of high average power and high peak power. This is a key point for ultrafast laser sources to be used in practical applications like particle acceleration and generation of EUV and X-ray sources. Two main approaches will be explored.

In the first approach, we will combine the very promising laser properties of Yb:CALGO and Yb:CaF₂ materials in oscillator and amplifier architectures suitable for high average/peak power operation. Explicitly, we will use these new crystals in the "Thin Disk" configuration, whose superiority in solving thermal problems has already been demonstrated by a high average power extracted from other crystals, both in oscillators and regenerative amplifiers. Collaboration with the University of Stuttgart, where the Thin Disk concept has been invented, has recently been initiated on this subject. We will also study the advantage of cryogenic cooling of these crystals in order to increase their thermal behaviour.

The second identified way to design efficient high peak/average power sources is the use of femtosecond Yb-doped fiber amplifier in the sub-100 fs pulse regime. Obtaining such short pulses with high energies requires a deep understanding and careful control of all the nonlinear effects that occur in the propagating core. An already on-going project aims at designing a fiber based source dedicated to the generation of high harmonics in gas at high repetition rate. The techniques used to reach this aim involved nonlinear propagation regimes, chirped pulse amplification, and active control of the phase of the pulses (Dazzler or SLM).

Furthermore, an important new project has just started in September 2008 on the development of the front-end (<10 fs, 100 mJ, 10 Hz) of the 20 PW laser from the "Institut de la Lumière Extrême / Projet Apollon". The ELSA team is responsible of the front-end workpackage of this ambitious project involving several laboratories from the Plateau de Saclay under

coordination of LOA. We will benefit from our strong knowledge in short pulse amplification, non-linear optical parametric effects and diode-pumped solid-state lasers to develop a front-end with unprecedented performances. The output pulses from the front-end system will then be amplified in large Ti:Sapphire amplifier disks to reach 20 PW peak power, opening up a whole new research area in high field laser-matter interaction.

BIOPHOTONIC APPLICATIONS

The ELSA team will pursue the development of new optical imaging techniques for Biophotonics using the specific properties of light sources such as low coherence for in-vivo imaging in scattering media through Optical Coherence Tomography, the spatial confinement of the evanescent wave for Total Internal Reflexion Imaging Microscopy, the high peak power and short duration of pulses for Fluorescence Lifetime Imaging and Light-Tissue Interaction.

Our activity on Biophotonics will continue to benefit from our collaboration with the "Centre de Photonique Biomédicale de l'Université Paris-Sud" in the "Laboratoire de Photophysique Moléculaire" through further development of the Total Internal Reflection Fluorescence Lifetime Imaging Microscopy (TIRFLIM) technique with white-light excitation. We will concentrate our study on protein-protein interaction involved in Alzheimer's disease. We will also start a new project on the development of a new far-field fluorescence microscopy technique, with a spatial resolution below the Abbe's diffraction barrier ($100 \text{ nm} \times 200 \text{ nm}$, lateral \times axial). The technique will be based on the principle of stimulated emission depletion microscopy (STED microscopy), with the originality to use a tunable excitation source, as already used in the TIRFLIM experiments. The ability to change the optical wavelength of both the excitation and desexcitation beams is crucial in order to be able to excite the large variety of fluorophores commonly used for cell imaging.

With the recent recruitment (September 2006) of Arnaud Dubois as a Professor at IO-GS, we have started to develop new high resolution optical imaging experiments based on full-field optical coherence tomography (OCT). In order to increase the image acquisition speed for *in vivo* applications, we will continue to work on new high power broadband sources based on spectrally-combined LEDs or Ti:Sapphire fluorescent multimode waveguides. Non-linear microscopy based on two-photon fluorescence excitation and harmonic generation will be developed and coupled to full-field OCT to provide images with different contrasts.

Based on our deep understanding of the ultra-short laser physics and technology (in the field of fiber amplifiers, dispersion management, non linear interaction), we will develop new laser architectures for biomedical applications, especially in ophthalmology and cancer detection areas.

Femtosecond lasers operating at $1 \mu\text{m}$ are widely used in LASIK experiments to create a thin flap before reshaping the eye cornea (by using excimer laser at 193 nm) in order to correct vision deficiencies, mainly myopia. However, in the case of pathologic cornea, femtosecond lasers at $1 \mu\text{m}$ cannot be used efficiently because of the strong scattering occurring in the oedematous tissue. To solve this problem, in 2007 we initiated work on the development of a femtosecond laser based on erbium doped fiber amplifier emitting above $1.6 \mu\text{m}$ to reduce scattering and to obtain high quality corneal surgery. This project is being pursued in collaboration with the LOA, Hôtel Dieu and two companies: Imagine Eyes and Amplitude Systèmes. The innovations in the design of the erbium doped fiber amplifiers in order to operate at high energy above $1.6 \mu\text{m}$ have been patented in autumn 2008.

In the continuity of our activity on corneal surgery, a new research project on glaucoma surgery will start in 2009. The objective is to develop a new tool for glaucoma surgery based on a compact infrared femtosecond laser operating in the optical transparency window at $1.7 - 1.8 \mu\text{m}$. Furthermore, an in situ real-time imaging system based on infrared optical coherence tomography for a careful control of the penetration depth of the femtosecond laser beam in the sclera will be developed. This project will extend our collaboration with the LOA, Hôtel Dieu and Amplitude Systèmes. This project is a clear illustration of the complementary skills on lasers and imaging techniques within the ELSA team.

Ultrafast lasers can also be used for fluorescence lifetime imaging due to the short excitation pulse duration. In this research area, we are starting a new project on the prostate cancer detection. The aim is to develop a fluorescence and ultrasound multimodality imaging to improve the quality of prostate biopsies. This project is being pursued in collaboration with the CEA-LETI (Grenoble), laboratory CREATIS (Villeurbanne), Centre Hospitalo-Universitaire Bordeaux and the two French companies VERMON (Tours) and Amplitudes Systèmes (Bordeaux). Our work will concern the development of a picosecond laser source operating at 780 nm based on erbium-doped fiber technologies followed by frequency doubling stage.

EVOLUTION OF FUNDING AND PERSONAL RESOURCES

We have secured the funding of our research activities scheduled for the next three years and a detailed list of the present research grants from national and international agencies is given in our activity report. Moreover, three new ANR projects have just started in January 2008 on "Laser for cancer detection by fluorescence", "Coherent combining of fiber amplifiers" and "Two-frequencies optically pumped semiconductor lasers". Several new grants have been recently obtained: an ANR project on "Laser and imaging for glaucoma surgery", a CNano project on "Blue lasers for bio-sensors nanoparticles", a CNRS grant on "High power thin disk femtosecond laser", a LNE grant on "High power 852 nm semiconductor lasers" and a grant from the DGA-French Army by the end of 2008 on "High power crystal fiber lasers at $1.6 \mu\text{m}$ ".

Concerning the members of the ELSA team, Gérard Roger (CNRS Research Engineer) will retire by the end of December 2008. The ELSA team will then be based on 6 permanent researchers (2 Professors, 1 Assistant Professor, 1 CNRS senior researcher and 2 CNRS junior researchers). Dimitris Papadopoulos (formerly post-doc scientist at ELSA) has obtained a three-year position from the Ecole Polytechnique in order to develop at the LCFIO the front-end of a PW laser in the frame of the "Institut de la Lumière Extreme" (see above). In September 2008, and for a two-year period, a post-doc scientist, Shifeng Jiang, has started to work on coherent combining fiber amplifiers.

Concerning PhD students, 4 new students will start in autumn 2008: Igor Martial, in collaboration with the French company Fibercryst (CIFRE funding), will work on crystal fiber based lasers, Clara Saraceno, in collaboration with the French company Teem Photonics (CIFRE funding), will work on picosecond ytterbium doped fiber amplifiers injected by passively Q-switched microchip lasers, Vivianne Devauges, in collaboration with the LPPM Orsay and within the "Centre de Photonique Biomedicale", will work on fluorescence lifetime microscopy (Ministry of Research funding) and Guillaume Bloom, in collaboration with Thales RT (CIFRE funding) will work on brightness improvement of infrared quantum cascade semiconductor lasers.

6.2 – MATERIALS, COMPONENTS AND SYSTEMS FOR BIOPHOTONICS (MACSYBIO TEAM) PROJECT

The "Materials, Components and Systems for Biophotonics", MacSyBio, research activity prospective is focussed on non conventional plasmonic imagery study and use in dynamical biochip systems in view of biomolecular interaction kinetic characterizations.

Our work is thus focused on four main aspects:

- plasmonics in, homogeneous and inhomogeneous, ordered and disordered, media structured at different scales,
- continuous instrumental development in order to increase the potential parameters/dimensions that can be measured using Surface Plasmon Resonance Imaging (SPRI),
- application to the study of biomolecular interactions, in particular using the model case of DNA:DNA interactions,
- dissemination and valorisation.

Many fields are involved in such dynamic biochip systems. This research activity being very multi-disciplinary will thus be carried out, as in the past, with the support of many collaborations.

So far, our work implementing the plasmonic imagery has been primarily based on non localized plasmon waves propagating on an quasi-infinite metal-dielectric interface. **We wish to investigate deeper, from a plasmonic point of view, the case of localized plasmons on metallic nanostructures, as well as the continuum of possibilities including spatially modulated propagating plasmons and coupled localized plasmons.**

To reach these goals, **nano-structuration** of the biochip metallic and/or organic films will have to be realized on micro-milli- meter scales (mainly new collaborations within Institut d'Optique and outside with partners such as Institut d'Electronique Fondamentale, LPN, laboratory Femto-ST in Besançon, ...) and the **multidimensional approach** measuring the reflectivity as a function of space, coupling angle, wavelength and propagation direction $R(x, y, \theta, \lambda, P)$ will have to be even better mastered to further increase characterization potential as well as the data precision and reliability.

Such nano-structuration will allow "texturing" the evanescent field and should open the route towards new generations of SPRI biochip sensor surface, where the biomolecular probes would be colocalized with the "hot spots" inducing stronger effects on the plasmon coupling when interacting with given targets, allowing new sensor chips with lower limit of detectability.

This nano-structures will also give us the possibility of investigating their specific **plasmon propagation**. The new insight gained on artificially structured biochip will help better interpreting the data obtained on biochip systems where biomolecular events are by nature inhomogeneous at different scales.

The possibility of characterizing the surface anisotropy will also allow us to study the **micro-fluidic effects** (new collaboration with Laboratoire de Photophysique Moléculaire and LPN). This will be done as example of application of such "biomolecular film anisotropy" measurement possibilities. It will help characterizing new fluidic devices and in turn participate in the development of fluidic system adapted to the biochip/lab on a chip (LOC) devices for which (micro-)fluidic is mainly responsible for distributing the potentials targets to the probes localized on the surface of the biochip.

To better characterize the surface dynamics and increase the spatial resolution beyond that conventionally achieved using propagating plasmons, a **fluorescent microscopy capability will be added** to our most complete SPRI system. Such innovative set-up will also allow us to directly compare of SPRI and classical fluorescence biochip systems.

In order to better control the targets:probes interactions as well as the biomolecular film construction, we are going to introduce yet another physical parameter: the **electrostatic potential**. Indeed, many of the biomolecular species, including DNA, are electrically charged and can thus be attracted or repelled using such electrostatic field parameter.

As far as applications are concerned, we will mainly follow two goals: one is completely new: we shall open part of our research facility to colleagues of other fields, in particular chemistry, biology, medicine, ... as an accessible **platform** with spotting, characterization and analysis capabilities; this will allow to disseminate our current and future results, and should induce new collaborations with new physical and bio-chemical questions yet to be formalized and answered. The second goal

is a follow up of a project we have already attempted to fund at national and European levels, namely valorising the SPRI capabilities we have demonstrated in dynamically differentiating DNA sequence at single nucleotide polymorphism (SNP) level into a **fully automated system**, fast, low cost and local, for genetic analysis of DNA signatures (many partners involved, academics and industrials). Our medical model case will focus on genetic illness such as cystic fibrosis and beta-thalassemia.

Concerning valorisation, the small company GenOptics, that was funded seven years ago as a spin off of our team, will remain a privileged partner.

In this context, we will pursue our work on the necessary **bio-functionalization** of the metallic film substrates and will follow up on the physical and chemical study of **DNA:DNA interactions**, which we have chosen as model case of biomolecular interactions.

CHAPTER 7 – FUTURE PROSPECTS OF THE OPTICAL SYSTEMS AND COMPONENTS GROUP (SCOP)¹⁴

Heads: Pierre Chavel, Directeur de Recherche and Raymond Mercier, maître de conférences

Faculty and Research Faculty holding permanent positions

Franck Delmotte, maître de conférences, head, team XUV Optics
François Goudail, professeur des universités
Sébastien de Rossi, maître de conférences
Hervé Sauer, maître de conférences
Jean Taboury, professeur des universités, head, team SpIm
Françoise Varnière, maître de conférences

Engineers, technicians holding permanent positions

Arnaud Jérôme, assistant ingénieur
Christiane Vergilino, technicien de recherche

Doctoral students already present at the time of this writing and who not expected to graduate before the end of 2009

Céline Pasanau	CIFRE, since 2007
Noura Ayari	CIFRE, since 2008
Frédéric Diaz	CIFRE (TRT), since 2008
Marius Peloux	CIFRE, since 2008
Charles Bourassin-Bouchet	allocataire, since 2008

Visiting scientists and post-doctoral fellows

Tsuyoshi Konishi, associate professor, Osaka University, 2009-2010 (planned)

Associate scientists contributing part time to the research of the group:

Nelson de Oliveira, research engineer, synchrotron Soleil
Bruno Pardo, former maître de conférences
Luc Dettwiller, teacher

¹⁴ See list of acronyms and explanations page 10

7.1 – SCOP, INTRODUCTION

7.1.1 – AMBITIONS OF THE GROUP

As long as it is clear that Institut d'Optique spans the broad field of Optics and teaches it to its students, the SCOP group is definitely a fundamental component of Institut d'Optique. There is no doubt that passive – perhaps also adaptive – optical systems will remain part of the profession of Optics and Photonics and that new systems will emerge as new technologies become available. The SPIm and XUV teams (sections 7.2 and 7.3 respectively), as can be seen from their projects below, have clear perspectives based on their current manpower. While activity on the aspherisation of optical surfaces will directly depend on partnerships that can be supported financially, optical surface metrology needs additional dedicated permanent manpower to be maintained (subsection 7.1.2). It is the ambition of the group leader not only to keep these topics active at the best international level, but to extend them through a closer link between LCFIO and the IO-GS engineering research division IOtech. The transverse skills on optical modelling and on metrology must be organised in a more efficient way, which implies additional manpower. A reinforced capacity to respond to partnership opportunities with industry on engineering projects ahead of industrial R&D will need to be established, in particular by recruiting research engineers to work on industrial partnership contracts. In the present situation of research in France, this means that a fraction of our staff, in addition to the doctoral students who are already in that situation, might well be employed in non permanent positions in the future.

7.1.2 OPTICAL SURFACES

The metrology of optical surfaces and their aspherisation by broad ion beam milling will remain active in the group, in spite of the fact that the uncertainties concerning the manpower of the team in the near future make the provisions fairly hazardous.

The activity in the field of metrology will be pursued in three directions:

- As partners of the ANR CAN, we shall be in charge of the final metrology of a device composed of 79 rectangular elements, giving 220 individual steps, the heights of which will range from 100 nm to 100 µm. The aim is to measure these 220 individual steps with a precision ideally of a few nanometres. It will associate white light interferometry, interferometric autocollimation and phase shifting interferometry.
- We shall pursue the study of a self-calibrated phase-shifting technique, which presents the advantage of not requiring an identical phase-shift between each interferogram. This method is therefore particularly interesting for large components or working in harsh conditions.
- We shall also pursue the theoretical study of a novel method of testing "transmission spheres" (spherical flat associated to an optics, used to test spherical surfaces). We have already done purely experimental tests of the method, which showed a sub-nanometre reproducibility. For the moment, the method only gives a profile of the departure from the best sphere. The theoretical study will show if it is possible to extract more information concerning the defects of the flat, ideally to obtain a bidimensionnal map.

As to aspherisation by broad ion beam milling, we have the support of CNES in order to develop off-axis aspherisation. The basic idea is to apply the aspherisation to an off-axis rotating spherical substrate. The aim is to achieve the same degree of precision and low roughness as we obtained for the STEREO EUVI axi-symmetrical mirrors. If successful, the technique would be applied to the manufacturing of the mirrors for the off-axis telescopes of the ESA Solar Orbiter mission, in collaboration with the thin film team for the XUV multilayers and the IAS solar team for the design of the instruments.

7.2 – SPIM

Our team has been created in 2004. During this four-year period, its activity has stabilized around three themes: Fourier transform (FT)-based hyperspectral imaging, polarimetric imaging and wavefront engineering. These topics are closely interconnected, in particular they all require image and signal processing. Consequently, progress in one of these domains can fertilize the others. This is important for a small team like ours. Our approach is to take into account the physical properties of the scenes, optics and signal processing for the design of innovative imaging systems. This approach applied to the three above mentioned topics presents many perspectives that we enumerate below.

7.2.1. MULTI- AND HYPER- SPECTRAL IMAGING

We have succeeded in the design and demonstration of a FT-based Hyperspectral imager CaHyD. However, it was only a validation of the concept. The final goal of this study is the design of a high-resolution imaging spectrometer in the infrared (bands II and III). This involves the following main aspects:

- A crucial issue is the evaluation of performance of a FT-based hyperspectral imager in terms of signal to noise ratio and of spatial and spectral resolution. In such systems, the construction of the spectrum is indirect, thus the influence of measurement noise on SNR and resolution is very different from what happens in classic, dispersive imagers. This issue is also crucial to determine the ability of such imagers to solve applications. The company Thales is interested by this study and finances a PhD who will address these issues. During the PhD the experimental validation will be done in collaboration with ONERA.

- Other concepts of compact systems situated near focal plane or using multiple apertures are of great interest. A PhD is planned with ONERA to study the physical and optical aspects of the first issue. The second issue will be addressed with Sagem D.S. with a DGA support.

7.2.2. POLARIMETRIC IMAGING

The originality of our approach is to combine optical design and precise characterization of signal processing performance of polarimetric imagers. We will go on developing both applications and theory aspects.

- Application to imagery of diffusely scattering material by combining polarimetric and multispectral imaging.
- Application to imagery through turbid media.
- Detection, definition of the contrast in OSC images.
- Application of a rigorous signal processing approach to more complex polarimetric imaging systems.

To perform this, we will reinforce collaborations with national and international teams that develop polarimetric images complementary to ours.

7.2.3. WAVEFRONT ENGINEERING

This topic is closely related to industrial needs. We will continue our existing collaborations and develop new ones.

- Pixellated optics: A third PhD student should be recruited this year to work more specifically on ophthalmic applications, namely, relating the defects of images with psychovisual quality.
- We will start an activity on optimization of wavefront coding masks. Our objective is to take into account the specificities of the final application (human observation, automatic detection, ...) to optimize phase masks. This work will be done with Thales Research and Technologies.
- We will continue with ONERA the investigation of non conventional coded multi aperture system placed near focal plane. We will study and design multi aperture phase patterns to optimize information extraction, which is in this case detection of discrete high intensity areas .

7.2.4. CONCLUSION

We have many projects to develop. For this development, the main issue is the critical size of the team. It is composed of three “enseignants-chercheurs”. We have diversified activities thanks to cooperation with a reasonable number of partners. However, in order to be stable, we would need to recruit at least one chercheur or enseignant-chercheur during the next 4 year period.

Another important aspect is the location: our team is still located in the old building of the Institute, which is a problem for our visibility with respect to colleagues and students. We hope to be able to move to the new location of the Institute as quickly as possible.

Finally, the research topics of the team have significantly evolved during the past years and now go far beyond “Spectro-imagerie”. We thus feel that our name should take into account this evolution. We propose “Systèmes d’imagerie et physique des images”, which is representative of the activity of the team and has the further advantage of keeping the same acronym: SPIIm !

7.3 – XUV OPTICS

In the near future, our research efforts will be focus on the study and development of new EUV components based on aperiodic or multiperiodic multilayers. The main applications concern the physic of attosecond pulses, astrophysics and dense plasma diagnostics (LMJ, LaserIX).

Concerning mirrors for astrophysics, we are involved in the EUI European consortium for Solar Orbiter mission. This ESA mission plans to study the surface of the Sun with an orbit that comes up to 0.2 astronomic units. The constraints imposed upon the instruments by the mission profile are very severe. It is necessary to design EUV instrumentation with high reflectivity and good spectral selectivity while minimizing the mass, the volume and the heat input. In this context, multilayer mirrors able to select two emission lines with high rejection of unwanted lines provide a means to reduce the mass of the payload and to minimize the area of the entrance aperture in the heat shield. In collaboration with IAS, we will continue our study on dual channel mirrors in order to improve the performances and stability of such coatings. We plan to design new multilayer stack by incorporating low absorption materials as Al or Mg and to performed a comparative study between two deposition techniques available in our laboratory: ion beam sputtering and DC/RF magnetron sputtering.

Concerning mirrors for attosecond pulses, we coordinate two complementary projects that have just started: one ANR project in collaboration with the Laboratoire de Chimie Physique – Matière et Rayonnement (P. Jonnard, Université Pierre et Marie Curie) and one RTRA “Triangle de la Physique” project in collaboration with CEA Saclay (P. Salières). The aim of these projects is to design and study theoretically and experimentally multilayer atto-mirrors, by using reliable optical constant values measured by XUV interferometry. That requires also optical and physico-chemical characterization of thin film materials. Interferometric system allows a direct determination of the index of refraction. Such tool requires the knowledge to design very great quality instrument, because of the narrow tolerances in this spectral range (mechanical assembly and

polishing of optic). A wave front division interferometer was recently demonstrated and our project will be strongly based on this unique ability of the Institut d'Optique. In order to optimize these atto-mirrors we will study the influence of the deposition conditions on the indices and on their optical properties. Comparisons between measurements and simulations using the measured index will allow a better understanding of component defects (interface, roughness, purity) and of their influence on atto-mirror optical properties. These results will be applied to produce new components for attosecond pulses as tuneable chirped mirrors that will be characterized on attosecond source at CEA Saclay. Even if the main part of this project deals with the determination of thin film optical constant and the design and realization of new optical component, the expected results will be very useful in other scientific fields and for other domains of application in the XUV. For example, the accurate determination of indices dispersion spectra near absorption thresholds will allow to check the validity of theoretical approach used to calculate optical constant. More generally, we think that our project will contribute to a better understanding of photon-material interactions at intermediate wavelengths ranging from x-ray to ultraviolet. Moreover, improvements made in the design of atto-mirror will be very useful for designing other important XUV components and systems: astrophysics mirrors (solar imaging), transmission filters for HHG sources, optical component for x-ray lasers sources (beamsplitters, filters, polarimeter, ...), diagnostics for dense plasmas. These applications imply several other french laboratories as: Institut d'Astrophysique Spatiale d'Orsay, Laboratoire d'Optique Appliqué de Palaiseau, Laboratoire d'Interaction des X Avec la Matière, CEA DAM de Bruyère le Chatel.

In most of EUV applications, multilayers are exposed to high flux sources or submitted to thermal cycling, and their performances can be limited by damages or aging. It is important to understand the degradation mechanisms (chemical reactivity, erosion by high energy particles, interdiffusion, surface contamination, stress relaxation...) in order to design new multilayer structures with optimized interfacial barrier layers and capping layers. Following the PhD collaboration established between IO, Sagem Défense Sécurité and CNES, we will pursue our efforts to develop new coating for EUV lithography collector optics. In this context, LCFIO is going to acquire an innovative characterization tool: Grazing X-ray Reflectometry (GXR) with micro-focus source. GXR is a powerful technique to study nanometric layer stacks. It allows the determination of the thickness and the interfacial roughness, and the complex index at the source wavelength of each of the successive films deposited on the substrate. The micro-focus source will allow local characterization and also measurements on curved optics or on laterally graded multilayers. These studies are intended for industrial transfer within Sagem company.

The VUV range (typically 60-120 nm), where we maintain unique experience in the design of components with as much reflectivity or polarizing capacity as can be hoped for given the strong absorption of matter in that range, will remain active for partnership with the solar astronomy and physical metrology communities.