# M2 QLMN – Track "Light and Matter"

The M2 QLMN: Quantum, Light, Materials and Nano Sciences offers a specialization through three tracks with transversal courses addressing fundamental concepts, and courses more in relation to the chosen orientation.

The track "Light and Matter" is described hereafter.

UE core + electives correspond to a total of 39 ECTS while the research internship for a duration of 18 weeks minimum corresponds to 21 ECTS.

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* LM=Light and Matter ; CM = Condensed Matter and its Interfaces ; ND = Nanodevices and Technologies

# M2 QLMN-Track « Light and Matter”

## Core UE (6 UE=18 ECTS)

**Choice of 6 UE among 9** (cliquer sur le cours pour aller sur sa fiche)

| | | Track* | Localisation | Hours |
|---|---|---|---|---|
| Light Matter interaction | 3 ECTS | LM / CM | IOGS | 30 h exam included |
| Introduction to 2nd Quantization: from quantum optics to condensed matter | 3 ECTS | LM / CM | IOGS | 30 h exam included |
| Physics of Quantum Information: qubits, entanglement and decoherence | 3 ECTS | LM | IOGS | 30 h exam included |
| Non-Equilibrium Statistical Physics and Phase Transitions | 3 ECTS | LM/CM | CS | 30 h exam included |
| Laser Physics | 3 ECTS | LM | IOGS | 30 h exam included |
| Non-Linear Electromagnetism | 3 ECTS | LM | IOGS | 30 h exam included |
| Quantum molecular physics | 3 ECTS | LM | UFR | 30 h exam included |
| Optics Labwork | 3 ECTS | LM | IOGS | 27 h TP |
| Projet industriel en R&D (pour les CFA) | 3 ECTS | LM | Entreprise CFA | |

## Electives UE (7UE=21 ECTS)

**Choice of 7 UE among this list :** (cliquer sur le cours pour aller sur sa fiche)

| | | Track* | Localisation | Hours |
|---|---|---|---|---|
| Molecular Quantum Dynamics | 3 ECTS | LM | UFR | 30 h exam included |
| Ultracold Atoms and Quantum Simulators | 3 ECTS | LM | IOGS | 30 h exam included |
| Manipulation de Systèmes Quantiques Simples | 3 ECTS | LM | IOGS | 30 h exam included |
| Optical excitations and quantum optics at the nanoscale | 3 ECTS | LM/CM | IOGS | 30 h exam included |
| Fundamentals of Nanophotonics | 3 ECTS | LM/CM | IOGS | 30 h exam included |
| Optics Labwork 2 | 3 ECTS | LM | IOGS | 27 h TP |
| Quantum communication | 3 ECTS | LM | IPP Telecom Paris | 24 h exam included |
| Recent Experiments in Quantum Information | 3 ECTS | LM/CM/ND | IOGS | 30 h exam included |

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|---|---|---|---|---|
| Technologies quantiques : communication, calcul et capteurs | 3 ECTS | LM/CM/ND | CS | 30 h exam included |
| Near Field Microscopy | 3 ECTS | LM | IOGS | 24 h exam included |
| Technologie des Lasers | 3 ECTS | LM | IOGS | 24 h exam included |
| Biophotonics | 3 ECTS | LM | IOGS | 24 h exam included |
| Fonctions et intégration photonique | 3 ECTS | LM | IOGS | 24 h exam included |
| Optique adaptative | 3 ECTS | LM | IOGS | 24 h exam included |
| Optique de l'extrême | 3 ECTS | LM | IOGS | 24 h exam included |
| Impulsions optiques ultra-brèves | 3 ECTS | LM | IPP | 30 h exam included |
| Plasma Physics | 3 ECTS | LM | IPP | 30 h exam included |
| Structure Moléculaire et Transition Optique | 3 ECTS | LM | UFR | 30 h exam included |
| Dynamique réactionnelle photo-induite | 3 ECTS | LM | UFR | 30 h exam included |
| Ultracold Molecules and Rydberg atoms | 3 ECTS | LM | UFR | 30 h exam included |
| Quantum Sensing | 3 ECTS | LM/CM | ENS | 30 h exam included |
| Other UE from “Cond. Mat.” or “Nanodevices and Tech.” track | 3 ECTS | - | - | - |

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|---|---|---|
| Course code: | **Light Matter interaction** | Semester 1 |
| Contributes to: | M2 Quantum, Light, Materials and Nano Sciences (QLMN) - | |

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| Course director:<br>Course teachers : | David Clément and Jean-Sébastien Lauret | |
| Volume:<br>Period: | 27 Hours | **3 ects** |
| Assessment: | | |
| Language of tuition: | English | |

**Course Objectives:** The interaction between light and matter holds a central place in experimental physics, to manipulate and to probe properties of light and/or matter. This ranges from the early spectroscopic studies of solids to the emergence of quantum technologies and the manipulation of individual quantum systems.

This course provides a comprehensive introduction to the interaction between light and matter, from a modern and transversal view. Starting from the structure of matter (atoms, solids) and classical models (Lorentz, Einstein), a semi-classical description of light-matter interaction is introduced. Both systems with discrete levels of energy (atoms, molecules, defect centers, quantum dots, ...) and with band structures (solids, excitons, …) are considered, and their similarities and differences are illustrated. The role of quantum coherences and of the dissipation are discussed, with descriptions based on rate equations and Optical Bloch equations. The course covers the manifestations of light-matter interaction in modern research and quantum technologies.
(Non-linear optics and ultrafast dynamics with short light pulses are treated in dedicated, separate courses).

**Course prerequisites:** Atomic Physics (M1); Solid State physics (M1); Quantum mechanics

**Syllabus**

Introduction
  Atomic structure (H atom, atoms with several electrons); Electronic structure of solids (Bloch functions, band structure, electron-hole pairs)
Lorentz and Einstein models; illustration of coherent manipulation (Lorentz) and of rate equations (Einstein)
Semi-classical description of light-matter interaction; Rabi oscillations, coherent manipulation of discrete systems; out of resonance Rabi, passage to a continuum, Fermi golden rule, semi-classical dielectric constant in solids
Excitonic transitions / Dimensionality
Dissipation in discrete systems; Optical Bloch Equations; Coupling to a continuum and rate equations
Manipulation of three level systems; optical pumping, superpositions of coherent states and two photons transitions
Impulsion exchange between light and matter; optical trapping of particles et laser cooling force
Mollow triplet (examples in atomics physics, quantum dots); field confinement (Jaynes-Cummings); molecules/colored centers; illustrations with quantum technologies

**On completion of the course students should be able to:** The students will have acquired a broad knowledge of the light-matter interaction, both in dilute and condensed matter systems. Following this course, students can specialize by choosing appropriate elective courses focused on excitonic or atomic physics. This course opens the way to a PhD in the broad domain of light-matter interaction (cold atoms, solid state quantum optics, single molecule quantum optics, polariton physics, optical properties of new semiconductor materials etc.…)

**Textbooks/bibliography:**

- “Optical properties of solids” M. Fox
- “Fundamental of semiconductors” PY Yu & M. Cardona
- “Optical processes in Solids” Y. Toyozawa
- “Introduction to Quantum Optics: From the Semi-classical Approach to Quantized Light”, G. Grynberg, A. Aspect, C. Fabre – Cambridge Univ. Press, 2010 (in particular the first chapters describe the semi-classical approach and the Optical Bloch Equations)
- “Optical Resonance and Two-Level Atoms”, L. Allen, J. H. Eberly, Dover 1975.
- “The quantum theory of light”, L. Loudon, 3rd Ed. Oxford Press, 1997.
- Online lectures of C. Cohen-Tannoudji at Collège de France on Laser cooling and manipulation of atoms - years 1981, 1982 and 1983.
- Online lectures of J. Dalibard at Collège de France on Laser cooling of atoms - year 2014/2015.

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|---|---|---|
| Course code: | **Introduction to 2nd Quantization** | Semester 1 |
| Contributes to: | M2 Quantum, Light, Materials and Nano Sciences (QLMN) - | |

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| Course director:<br>Course teachers : | Guillaume Roux, Christoph Westbrook | |
| Volume:<br>Period: | 27 Hours | **3 ects** |
| Assessment: | Written exam | |
| Language of tuition: | English | |

**Course Objectives:** We Introduce the formalism and first applications. Starting from the quantization of the electromagnetic field, we discuss the emergence of quantum states without classical counterparts and two-photon correlation effects. The formalism is then extended to the quantization of matter for both Bose and Fermi systems. Some widely used approximation methods are discussed as well as their applications to superfluidity and superconductivity. The notions of quasi-particles and collective modes are introduced and some universal aspects resulting from the mapping between Bose, Fermi, and spin systems are discussed. Students will be asked to read and analyse some landmark papers in the field.

**Course prerequisites:**
Elementary quantum mechanics
Statistical physics

**Syllabus**

1. **Quantization of electromagnetic field.** Quantum harmonic oscillator, Coulomb gauge. Fock states, Coherent states, Thermal states. Means and and variances of observables in these states
2. **Interaction with a bound electron in the dipole approximation.** Time dependent perturbation theory. Stimulated emission and absorption, spontaneous emission. Connection to Einstein's treatment of BLackbody radiation. Inhibition of Spontaneous emission, Porcell factors.
3. **Single photon detection.** Photo electric effect, for a classical and a quantum field. Action of a beam splitter in terms of the fields
4. **Two photon detection.** Anticorrelation at beam splitter, antibunching. Hong Ou Mandel effect
5. **Second quantization of massive particles.** Bosons and fermions, two-particle case, Fock states and annihilation / creation operators, field operator, correlators and Green's function, Wick's theorem.
6. **Bose fluids.** Bose-Einstein condensation, the effect of interactions, Bogoliubov approximation for bosons. Introduction to phonons.
7. **Fermi fluids and pairing.** Fermi gases. Paired state and BCS wave-function, gap equation
8. **Quantum magnetism.** Spin models, spin-wave theory, Jordan-Wigner transform, quantum phase transitions.

There will be 4 or 5 homework problems to be worked at home.

**On completion of the course students should be able to:** read some of the basic literature and advanced textbooks in the field.

**Textbooks/bibliography:**

"Introductory Quantum Optics", C.C. Gerry and P.L. Knight, Cambridge Univ. Press (2005)

"Introduction aux lasers et à l'Optique Quantique", G. Grynberg, A. Aspect, C. Fabre, Ellipses, English version (september 2010) significantly updated "Introduction to Quantum Optics: From the Semi-classical Approach to Quantized Light"

"Quantum Mechanics, Volume 3: Fermions, Bosons, Photons, Correlations, and Entanglement", Cohen-Tannoudji, B. Diu, F. Laloë, Wiley
"Many-body problems and quantum field theory", Ph.A. Martin, F. Rothen, Springer

"Many-body quantum theory in condensed matter physics", H. Bruus, K. Flensberg, Oxford Press

"An introduction to quantum spin systems", J.B. Parkinson, D.J.J. Farnell, Springer

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| Course code: | **Physics of Quantum Information: qubits, entanglement and decoherence** | Semester 1 |
| Contributes to: | M2 Quantum, Light, Materials and Nano Sciences (QLMN) - | |

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| Course director:<br>Course teachers : | Antoine Browaeys and Laurent Sanchez-Palencia | |
| Volume:<br>Period: | 27 Hours | **3 ects** |
| Assessment: | Final exam + 4-5 problem sets and/or quizzes during the course that will be graded | |
| Language of tuition: | English | |

**Course Objectives:**

Qubits and our ability to control, manipulate, and measure them are the basic ingredients for the development of the emerging quantum technologies. Exploiting the most intriguing aspects of quantum physics, such as quantum superpositions and entanglement, they will allow us to perform tasks without classical counterparts such as the simulation of many-body systems or an unprecedented enhancement of the precision of sensors. The general framework to understand the potential of ensembles of quantum bits to perform such tasks lies at the crossroads of quantum physics and quantum information.

This course is an introduction to the physics of quantum information, from concepts to applications in quantum technologies, illustrated by the most recent experiments. These concepts are the common language of the four pillars of quantum technologies (communication, sensing, simulation, computation). Starting from the notion of qubit and its control using logical gates and quantum measurements, we show how to exploit it to perform elementary tasks. We then discuss the notion of entanglement and decoherence effects within an extended introduction to open quantum systems.

**Course prerequisites:**

A course in quantum physics at the level of, for example, the book “Mécanique Quantique”, J.L. Basdevant, J. Dalibard, and M. Joffre, Presse de l’Ecole Polytechnique. Available in English (Springer).

Although the course is independent from other ones, the concepts discussed in the lectures are related to the ones taught in the courses: “Quantum optics and second quantization” and “Light-matter interaction”.

**Syllabus**

- Notion of qubit, Bloch sphere, 1 and 2 qubit gates, non-cloning theorem.
- Implementations of qubits on physical systems.
- Quantum measurement theory, QND measurements, strong and weak measurements.
- Entanglement and density matrix. Application to teleportation.
- Von Neumann and Renyi entropies: Tomography, purity measurement.
- Introduction to open quantum systems within the Krauss/Lindblad formalism, quantum jumps.
- Physical content of the Lindblad equation: Relaxation towards equilibrium and driven systems, from Jaynes-Cummings to spontaneous emission, Wigner-Weisskopf approach.
- Stochastic wave functions.
- Decoherence and its control

We will use illustrate the concepts with the python environment QuTip (http://qutip.org).

**On completion of the course students should be able to:**

- Understand quantum physics from a modern perspective, using the language of quantum information.
- Have on overview of quantum information theory within the rapidly evolving field of quantum technologies.
- Read the more specialized literature related to recent experiments in the field.

**Textbooks/bibliography:** Notes provided by the lecturers.

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| Course code: | **Non-Equilibrium Statistical Physics and Phase Transitions** | Semester 1 |
| Contributes to: | M2 Quantum, Light, Materials and Nano Sciences (QLMN) - | |

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| Course director:<br>Course teachers : | Jean-Jacques Greffet<br>Denis Grebenkov | |
| Volume:<br>Period: | 27 Hours | **3 ects** |
| Assessment: | Written examination | |
| Language of tuition: | English | |

## Course Objectives:

Introductory courses on statistical physics deal with non-interacting particles in equilibrium. The first part of this course deals with nonequilibrium. The second part deals with interacting particles. Several approaches to non-equilibrium statistical physics will be presented: linear response theory, Langevin model, Boltzmann equation and irreversible thermodynamics. The role of inter-particle interactions and resulting collective phenomena such as phase transitions will be discussed.

## Course prerequisites:

Basic quantum mechanics, introduction to statistical physics

## Syllabus

Linear response theory
Fluctuation-dissipation theorem
Brownian motion: Langevin model
Introduction to transport phenomena
Boltzmann equation
Introduction to irreversible thermodynamics
Inter-particles interactions, Ising model
Mean field approximation, critical behavior
Order parameter, symmetry breaking
Examples of phase transitions

## On completion of the course students should be able to:

deal with nonequilibrium systems and systems of interacting particles. They should be able to extract information from correlations, master the key concepts of transport phenomena and phase transition.

## Textbooks/bibliography:

R. Balian, From microphysics to Macrophysics Vol.1 Springe-Verlag, Berlin, 1982
R. Balian, From microphysics to Macrophysics Vol.2 Springe-Verlag, Berlin, 1991
R. Kubo, M. Toda, N. Hashitsume, Staistical Physics II, Springer Verlag, Berlin, 1985

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| Course code: | **Laser Physics** | Semester 1 |
| Contributes to: | M2 QLMN – Track “Light and Matter” | |

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| Course director:<br>Course teachers : | Fabien Bretenaker (LAC)<br>Marc Hanna (LCF), Frédéric Druon (LCF), Thierry Ruchon (CEA) | |
| Volume:<br>Period: | 30 Hours (exam included) | **3 ects** |
| Assessment: | Final exam / midterm exam | |
| Language of tuition: | English | |

Course Objectives:
The course starts with a semi-classical description of light-matter interaction, and establishes Maxwell-Bloch equations. The rate equation approximation is used to provide operational principles of the single frequency laser. Starting from this description, transition broadening mechanisms, dynamical regimes, and noise properties of lasers are described. The spatial aspects are then examined, using paraxial transfer matrices to describe cavity stability and beam propagation. Finally, ultrafast lasers using mode-locking are studied along with related subjects such as the propagation and characterization of femtosecond pulses and attosecond pulse generation.

Course prerequisites: Undergraduate knowledge of electromagnetism and quantum mechanics. A first course in lasers helps, but is not required.

**Syllabus**

Matter-light interaction; Equations of the single-frequency laser
Single frequency laser in steady-state regime
Inhomogeneous line broadening
Transient and Q-switched operation
Noise properties of lasers
Mode-locking and ultrashort pulses
Optical resonators: ray matrices, Gaussian beams, cavity stability
Advanced topics in ultrafast optics : carrier-envelope phase and attosecond pule generation

**On completion of the course students should be able to:** understand and be able to describe the physical principles underlying laser operation in a wide variety of regimes.

**Textbooks/bibliography:** Lecture notes written by Fabien Bretenaker

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| Course code: | **Non-Linear Electromagnetism** | Semester 1 |
| Contributes to: | M2 QLMN – Track “Light and Matter” | |

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| Course director:<br>Course teachers : | François Hache (LOB)<br>Isabelle Zaquine (TPT), Marie-Claire Schanne-Klein (LOB) | |
| Volume:<br>Period: | 27 Hours<br>Semester 1 | **3 ects** |
| Assessment: | Final exam + Homework midterm exam | |
| Language of tuition: | English | |

**Course Objectives:**
Since the laser has been invented, optics opened a new dimension entering the nonlinear world with already numerous applications to light sources and optical processing of information. This course will introduce the students to this domain and enable them to fully master its innovative aspects. It describes the physics of the nonlinear interaction between light and matter from a perturbation approach and shows its consequences on the propagation of optical waves. Its describes in detail the second and third order non linear effects rich in applications.

**Course prerequisites:** Undergraduate knowledge of electromagnetism (linear regime, optical properties of anisotropic media…). A first course in nonlinear optics helps, but is not required.

**Syllabus**
I - INTRODUCTION TO NONLINEAR OPTICS
Basics of nonlinear optics
Physical origins of the optical nonlinearities

II - NONLINEAR WAVE EQUATIONS
Derivation of Maxwell’s equations – Constitutive relations
Linear wave equation : pulse response and linear susceptibility – anisotropic medium – transfer of energy – group velocity
Nonlinear susceptibilities : nonlinear pulse response and susceptibilities – properties of the nonlinear susceptibilities tensors
Nonlinear wave equations

III - 2nd ORDER NONLINEARITIES
Manley-Rowe relations
2nd Harmonic Generation : weak conversion, phase matching, strong conversion : SHG with pump depletion, phase matching in uniaxial crystal.
Quasi-phase matching in materials
Frequency Mixing, Optical parametric amplification and oscillation
Spontaneous parametric down conversion
Sources of entangled photons based on SPDC

IV - MICROSCOPIC THEORY of the NONLINEAR OPTICAL RESPONSE
Notion of polarizability and local field factor
Liouville equation: perturbation approach with the density matrix formalism
Calculation of the linear susceptibility
Calculation of X(2)
Calculation of the third-order nonlinear response function for resonant configurations
Introduction to the 2D spectroscopy

V - 3rd ORDER NONLINEARITIES
Four-wave Mixing
Optical Kerr effect : n2(I), optical bistability, self-focusing effect, self-phase modulation and solitons
Raman Scattering : spontaneous and stimulated Raman scattering, Raman amplification, Raman Laser
2 photons Absorption

On completion of the course students should be able to: understand and be able to describe the physical principles underlying various nonlinear interactions.

**Textbooks/bibliography:**
F. Hache, Optique non linéaire, CNRS-EDPSciences, Savoirs actuels, 2016.
Lecture notes available at http://paristech.iota.u-psud.fr/site.php?id=84
Robert W. Boyd, Nonlinear Optics, 4th Edition, Elsevier Ed
Butcher, P N. / Cotter, D., The Elements of Nonlinear Optics , Cambridge University Press.1993.
F. Sanchez, Optique non linéaire, Ellipses, 1999.

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| Course code: | **Quantum molecular physics and its application to molecular cooling** | Semester 1 |
| Contributes to: | M2 QLMN – Track “Light and Matter” | |

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| Course director:<br>Course teachers: | Cyril Falvo & Hans Lignier | |
| Volume:<br>Period: | 27 Hours | 3 ECTS |
| Assessment: | 1 exam | |
| Language of tuition: | French or English | |

**Course Objectives:**

For physicists, the studies of molecules cover a wide range of fields such as atmospheric sciences, astrochemistry, physical chemistry, laser physics. Molecules have a large number of degrees of freedom (electronic, vibrational and rotational) and involve a large variety of energy scales. It results in a complex energetic structure usually probed through spectroscopy. Although known to be difficult to manipulate, the last two decades have witnessed a spectacular development of experimental methods to control their degrees of freedom (cooling processes). This opens the way to new perspectives in quantum chemistry, in the development of quantum simulators and computers or in the improvement of fundamental physics tests.

The objective of this course is to give the basic theoretical tools to describe the quantum states of molecules and their interaction with laser fields and apply this formalism to the physics and chemistry of ultra-cold molecules. The first part of the class is an introduction to the quantum theory of molecules. Relying on the Born-Oppenheimer approximation an introduction to the theory of electronic structure calculation will be given. Then the theory of rotational and vibrational quantum states will be developed. In the second part of the class, we will review modern techniques to manipulate and cool molecules to low and ultralow temperatures.

**Course prerequisites:** Quantum mechanics (L3/M1) – Atomic physics (M1)

**Syllabus**

I. General introduction
II. Molecular structure and transitions
  II.1 Electronic structure of molecular systems
    II.1.a. Born-Oppenheimer approximation
    II.1.b. Electronic structure of H2+
    II.1.c. Introduction to electronic structure calculations (Hartree-Fock)
  II.2 Rovibrationnal structure
    II.2.a. Diatomic molecules
    II.2.b. Rigid rotator
    II.2.c. Non-rigid rotator
  II.3 Transitions in molecules
    II.3.a. Dipolar approximation
    II.3.b. IR and Raman spectra
    II.3.c. Franck-Condon principle
    II.3.d. Hönl-London factors
III. Cooling molecules
  III.1 Cold molecular beams
  III.2 Stark & Zeeman deceleration
  III.3 Cooling to ultralow temperatures

**On completion of the course students should be able to:**
Students will acquire the complex theoretical tools to describe the electronic and rovibrationnal structure of molecules. They will be able to identify the different physical processes occurring in a molecular systems and their interaction with light. They will also learn some of the current experimental methods used in the field of ultracold molecular physics.

**Textbooks/bibliography:**

- Quantum Mechanics, vol. 1 & 2, C. Cohen-Tanoudji, B. Diu, F. Laloë
- Molecular Quantum Mechanics, P. W. Atkins, R. S. Friedman
- Molecular vibrations, E. Bright Wilson, Jr., J.C Decius and Paul C. Cross
- Molecular Spectra and Molecular Structure, vol. 1, 2 & 3 G. Herzberg

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| Course code: | **Optics Labwork** | Semester 1 |
| Contributes to: | M2 QLMN – Track “Light and Matter” | |

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| Course director:<br>Course teachers ; | Fabienne Bernard (IOGS) | |
| Volume:<br>Period: | 27 hours | **3 ects** |
| Assessment: | Reports on each labwork | |
| Language of tuition: | English or French | |

Course Objectives:
Course based on strong emphasis on hands-on training, which is inseparable from top-level classroom training.
Labwork subjects intend to reflect the most recent advances in research in all areas of modern optics, and in state-of-the-art optical technologies.
The course provides opportunities to perform top-level labwork in quantum physics (source of entangled photons, saturated absorption), instrumental optics (adaptive optics, phase-shifting interferometer, etc.), lasers (holography, interferometry, optical parametric oscillators, etc. ) and optical telecommunications (erbium-doped fibre amplifiers, 10 Gb/s digital transmission).

Course prerequisites:

**Syllabus**

- **Quantum Photonics:**

*Entangled photons, Hong-Ou-Mandel effect, and Bell inequality* (use of single-photon-counter Modules, counters and coincidence detector. Photon pairs are obtained by spontaneous parametric conversion and, after adjustment of the EPR state, the photon coalescence or a violation of a Bell inequality can be observed).
*Saturated absorption* (Protocol of major interest in atomic physics in order to accurately lock the wavelength of a laser source).
*Second-harmonic generation in nonlinear crystals* (Principle of the second harmonic generation -SHG- effect in 2nd order nonlinear crystals).

- **Advanced Laser Technologies**

*Picosecond and femtosecond lasers* (Manipulation of short-pulse lasers, and temporal characterization of pulses by means of autocorrelation).
*Diode pumped Nd:YAG LASER* (Characteristics of the amplifying medium : measurement of the fluorescence - Laser effect at 1.06µm Q-Switch mode laser operation - Intra-cavity frequency doubling).
*Optical Parametric Oscillator* (Study of a tunable solid-state laser source. Nd:YAG laser-pumped optical parametric oscillator generating frequency-tripled nanosecond laser pulses).

On completion of the course students should be able to:
Handle experimental techniques and protocols essential in modern experimental physics.

Textbooks/bibliography:
http://www.institutoptique.fr/en/Education/Ingenieur-Grande-Ecole/Labwork

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| Course code: | **Molecular Quantum Dynamics** | Semester 1 |
| Contributes to: | M2 QLMN – Track “Light and Matter” | |

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| Course director:<br>Course teachers : | Éric Charron & Pascal Parneix | |
| Volume:<br>Period: | 27 Hours | **3 ects** |
| Assessment: | 1 exam, 2 home works | |
| Language of tuition: | English | |

**Course Objectives:**

This course, with hands-on exercise sessions, will provide a unified treatment for the understanding of quantum dynamical processes taking place in laser-matter interaction, with a particular emphasis on non-linear interactions and on ultra-short processes. This will include the control of atomic and molecular dynamics using external fields, quantum interferences between indistinguishable pathways, strong field non-linear physics and energy relaxation processes in the statistical limit. All phenomena will be introduced and explained from a time-dependent quantum mechanical perspective.

**Course prerequisites:**

Quantum Mechanics courses at the L3 and/or M1 level.

*Note*: Several “Hands-on” exercise sessions are provided during this course, as well as two homework problems.

*Evaluation policy*: Final marks will be based on the two homework assignments (40%), and on a final exam (60%). Collaboration, limited to two students, is allowed for each homework.

**Syllabus**

**I – Time-Dependent Quantum Dynamics**
Time-dependent Schrödinger equation, wave packets, quantum-classical correspondence, quantum revivals.

**II – Approximate Solutions of the Time-Dependent Schrödinger Equation**
Representations in quantum mechanics, time-dependent perturbation theory, adiabatic dynamics, sudden approximation, Wentzel-Fermi golden rule, time-dependent variational approaches.

**III – Numerical Methods in Time-Dependent Quantum Dynamics**
Spectral and pseudo-spectral representations, eigenstates and wave packets, Fourier methods and time-dependent propagation techniques, imaginary time propagations.

**IV – Molecular Dynamics in the Femtosecond ($10^{-15}$ s) Regime**
Born-Oppenheimer approximation, diabatic and adiabatic representations, potential energy surfaces, electronic structure of atoms and molecules, conical intersections, molecular vibrations/rotations, wave packet interferometry, time-delayed multiple-pulse excitation, transition-state spectroscopy, femtosecond molecular dynamics.

**V – Electronic energy relaxation in the statistical limit**
Quantum yield, non-adiabatic couplings, statistical limit and irreversibility, internal conversion, intersystem conversion.

**VI – Attosecond ($10^{-18}$ s) Processes and Strong Field Physics**
Multiphoton processes and strong field physics, above threshold ionization and dissociation, bond softening, population trapping, high harmonic generation, generation of attosecond pulses, recollision processes, attosecond physics in atoms and molecules.

**On completion of the course students should be able to:**

You will gain a good understanding of several theoretical and numerical methods used to describe the interaction of atomic and molecular systems with external fields in nowadays explicitly time-dependent experiments. The everlasting development of new light sources and of controlled time-dependent magnetic fields renders this knowledge a pre-requisite in today’s research in atomic, molecular and optical physics. At the end of this course you will be able to solve relatively simple time-dependent quantum problems analytically, and to design efficient numerical approaches for more complex situations.

**Textbooks/bibliography:**

**Quantum Physics:** Introduction to Quantum Mechanics: A Time-Dependent Perspective, D. J. Tannor ; Quantum Mechanics, vol. 1 & 2, C. Cohen-Tanoudji, B. Diu, F. Laloë ; Quantum Mechanics, L. I. Schiff.

**Atomic & Molecular Physics:** Atomic Physics, C. J. Foot ; Molecular Quantum Mechanics, P. W. Atkins, R. S. Friedman ; Coherent Dynamics of Complex Quantum Systems, V. M. Akulin.

| Course code: | **Ultracold atoms and quantum simulators** | Semester 1 |
|---|---|---|
| Contributes to: | M2 QLMN – Track "Light and Matter" | |

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| **Course directors:** | Marc Cheneau and Igor Ferrier-Barbut | |
| **Volume:** | CM: 27 Hours | **3 ects** |
| **Assessment:** | Weekly exercises, written exam (~3 hours, with documents) | |
| **Language of tuition:** | English | |

**Course Objectives:**

This set of lectures is an introduction to the modern many-body physics of ultracold atoms and to the notion of quantum simulators with neutral atoms.

The lectures will review the basic physics of non-interacting bosons and fermions, before diving in the description of interacting quantum many-body physics. The emergent collective phenomena of Bose-Einstein condensation and superfluidity will be described. We will study the different interactions that take place between cold atoms, that are needed to derive their many-body Hamiltonian. Then an example of a quantum phase transition and its observation in experiments will be presented through the superfluid-insulator transition in an optical lattice. Next, we will focus on examples of how quantum simulations of magnetism problems can be implemented experimentally. Finally, we will present numerical methods to predict the result of a quantum simulation experiment (in collaboration with the quantum simulation startup pasqal.io), and showcase the state-of-the art experimental methods in modern setups.

**Course prerequisites:**

- Introduction to second quantization
- Physics of quantum information
- Light-matter interaction

**Syllabus:**

- Statistical quantum physics: Bosons and fermions, Bose-Einstein condensation (BEC) of the ideal gas.
- Mean-field level description of a BEC: Phase coherence and excitations.
- BEC beyond the mean-field level: Bogoluybov transformation and quasi-particles.
- Superfluidity: Vortices, Landau criterion.
- Interactions in atomic systems: Effective contact interaction, long-range interactions.
- Simulation of a quantum phase transition: Bose Hubbard model, superfluid - Mott insulator transition
- Quantum magnetism in optical lattices: Spin exchange interaction, perturbation theory
- Numerical simulation of quantum many-body systems
- Step-by-step description of a quantum simulation experiment

**On completion of the course students should be able to:**

Read the more specialized literature related to recent experiments in the field.

Have a comprehensive understanding of the field of many-body physics with neutral atoms, and of the rapidly developing quantum simulation platforms.

**Textbooks/bibliography:**

L.P. Pitaevskii and S. Stringari, *Bose-Einstein Condensation and superfluidity* (Oxford Science Publication, 2016).

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|---|---|---|
| Course code: | **Manipulation de systèmes quantiques simples** | Semester 1 |
| Contributes to: | M2 QLMN – Track “Light and Matter” | |

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| **Enseignants:** | Rosa Tualle-Brouri (Institut d'Optique Graduate School)<br>Nina H. Amini (L2S, CentraleSupelec) | |
| **Volume horaire:** | 27h | **3 ects** |
| **Modalités d’évaluation:** | En plus de l’examen final (écrit), une petite partie du contrôle des connaissances porte sur des compte-rendus et des TDs. | |
| **Langue:** | Français | |

**Objectifs du cours:**

- 1ère partie : Rosa Tualle-Brouri : *Manipulation d'états quantiques de la lumière:*

Les objectifs sont d’étudier l’optique quantique et ses applications. Seront abordés : la nature du photon; l’amplitude et la phase au niveau quantique ; l’intrication ; la propagation du champ quantique dans les milieux matériels ; des notions d’information quantique ; ainsi que les techniques expérimentales associées.

- 2ème partie : Nina H. Amini : Stabilisation de systèmes quantiques ouverts par *feedback quantique*

Nous allons considérer des systèmes quantiques ouverts soumis à des mesures non-destructives. Nous présentons des méthodes de Lyapunov stochastiques afin de stabiliser des états quantiques pures qui sont des états propres des operateurs de mesures.

**Pré-requis:**
Des pré-requis de base en mécanique quantique sont nécessaires comme par exemple décrits dans le livre Mécanique quantique (Cohen-Tannoudji, Diu, Laloë).

**Contenu du cours**

**I – Quantification du champ électromagnétique** (Rosa Tualle-Brouri, 3 heures)
- Nature du photon – espace de Fock - Etats cohérents
- Action d’une séparatrice – coalescence de photons
- Quadratures - tomographie quantique - fonction de Wigner
- Problèmes multimodes – interférences à 1 photon

**II – Propagation du champ quantique dans les milieux matériels** (Rosa Tualle-Brouri ~ 7,5 heures)
- Etude de l’amplification paramétrique optique
- Génération de vide comprimé – paires EPR
- Génération conditionnelle d’états quantiques
- Applications à l'optique quantique: intrication, inégalités de Bell, téléportation, opérations fondamentales du calcul quantique, finalité du calcul quantique.
- Etude du problème multimode, modélisation en temps continu. Application au cas d’une source de photons uniques.

**III - Système ouvert soumis à des mesures non-destructives** (Nina H. Amini ~ 3 heures)
- Systèmes ouverts
- Mesures quantiques non-destructives
- Trajectoires quantiques
- Cavité QED: Exemple de système ouvert soumis à des mesures QND en temps-discret

**IV – Stabilisation d’états « nombre de photon » pour une cavité QED** (Nina H. Amini ~3 heures)
- Cavité QED soumise à des mesures non-destructives imparfaites
- Comportement asymptotique en boucle ouverte (sans contrôle)
- Feedback basé sur la mesure
- Stabilisation par des méthodes de Lyapunov

**V – Stabilisation de systèmes de moments angulaires quantiques soumis à des mesures QND** (Nina H. Amini ~3 heures)
- Systèmes quantiques ouverts en temps continu
- Mesure non-destructive Homodyne
- Exemple : Systèmes de moments angulaires quantiques soumis à des mesures QND en temps continu
- Comportement asymptotique sans contrôle
- Feedback basé sur la mesure
- Stabilisation par des méthodes Lyapunov stochastiques

**Compétences attendues à la fin de l’UE:**
A la fin du cours un étudiant doit pouvoir lire et expliquer les articles récents dans le domaine du contrôle quantique, particulièrement pour ce qui concerne les travaux en relation avec l’optique quantique.

**Bibliographie:**
Des notes de cours seront distribuées.

-J-M. Raimond and S. Haroche. Exploring the quantum : atoms, cavities, and photons. Oxford University Press, 82 :86, 2006.
-H. M. Wiseman and G. J. Milburn. Quantum measurement and control. Cambridge university press, 2009.

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|---|---|---|
| Course code: | **Optical excitations and quantum optics at the nanoscale** | Semester 1 |
| Contributes to: | M2 Quantum, Light, Materials and Nano Sciences (QLMN) - | |

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|---|---|---|
| Course director:<br>Course teachers : | J. Bloch (C2N), E. Deleporte (ENS-Paris-Saclay),Sylvain Ravets (C2N) | |
| Volume:<br>Period: | 21 Hours | **3 ects** |
| Assessment: | Written exam 3h | |
| Language of tuition: | English | |

**Course Objectives:**

The course aims at describing light-matter interaction in condensed matter systems in close connection with on-going state of the art research. It constitutes the logical continuation of the Light-matter interaction course for people interested in condensed matter systems. It focuses on semiconductor nanostructures and their use to tailor light matter interaction, realize sources of quantum light and explore quantum fluids of light.

**Course prerequisites:**

**Syllabus:**

In quantum confined semiconductors, the elementary excitations created by the absorption of a photon is an exciton. The course starts with a description of these elementary excitations in different condensed matter systems. The description is illustrated both using textbook examples from the history of semiconductors as well as recent publications related to the advent of new materials. The second part of the course is dedicated to cavity quantum electrodynamics (CQED) using solid-state quantum emitters embedded in integrated high finesse cavities. The properties of quantum dots (fermionic systems behaving as artificial atoms) and their use as bright sources of quantum light will be discussed. Then we will discuss how quantum wells in microcavities provide a platform for the exploration of quantum fluids of light.

Part I: Semiconductor nanostructures and excitons (2x3h)

- Excitons in inorganic and organic semiconductors, Excitons in hybrid semiconductors (perovskites),
- Influence of the dimensionality: heterostructures, 2D materials
- Control of the exciton properties using electric field, magnetic field

Part II: Cavity Quantum Electrodynamics at the nanoscale (5x3h)

1) Quantum emitters
- Quantum dots: Carrier confinement, Spectrum of emission, Single photon source
- Quantum dots in cavity: semiconductor microcavities, Purcell effect, bright source of single photons

2) Quantum fluids of light
- Excitons in 2D: selection rules, bosonic properties; effective mass for photons in 2D; Exciton photon strong coupling
- Quantum fluids of light. Polariton dispersion; Interactions (Gross Pitaevskii equation). Discussion of experiments: superfluidity, Bose Einstein condensation, Lattices (ex: polariton graphene)

**On completion of the course students should be able to:**

**Textbooks/bibliography:**

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|---|---|---|
| Course code: | **Fundamentals of Nanophotonics** | Semester 1 |
| Contributes to: | M2 Quantum, Light, Materials and Nano Sciences (QLMN) - | |

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|---|---|---|
| Course director:<br>Course teachers : | Jean-Jacques Greffet<br>Henri Benisty | |
| Volume:<br>Period: | 27 Hours | **3 ects** |
| Assessment: | written exam | |
| Language of tuition: | English | |

**Course Objectives:**
The goal of the course is to provide an introduction to the research topics in the field of nanophotonics. To achieve this goal, the course discusses the main concepts, structures and tools used to generate, detect and manipulate light at the nanoscale.

**Course prerequisites:**
Knowledge of Maxwell equations in material media, complex refractive index, reflection and refraction, guided waves.

**Syllabus**

Introduction to near-field optics: angular spectrum, evanescent waves.
Super-resolution imaging: breaking the diffraction limit.
Theory of electromagnetic fields at the nanoscale: scattering, Green tensor and local density of states.
Propagating surface plasmons.
Localized surface plasmons.
Tailoring spontaneous emission and scattering with antennas and cavities.
Propagation in periodic media: homogenization.
Propagation in periodic media: photonic crystals.
Metamaterials and metasurfaces.

**On completion of the course students should be able to:**
At the end of the course, the student will be able to read research papers on nanophotonics.

**Textbooks/bibliography:**
L. Novotny, B. Hecht, Principles of nano-optics, Cambridge University press, 2012
H. Benisty, J..J. Greffet, P. Lalanne, Introduction to Nanophotonics, Oxford University Press, 2022

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|---|---|---|
| Course code: | **Optics Labworks 2** | Semester 1 |
| Contributes to: | M2 QLMN – Track "Light and Matter" | |

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|---|---|---|
| **Course director :**<br>**Course teachers :** | Fabienne Bernard (IOGS) | |
| **Volume:** | 27 hours | **3 ects** |
| **Assessment:** | Reports on each labwork | |
| **Language of tuition:** | English or French | |

**Course Objectives:**
Course based on strong emphasis on hands-on training, which is inseparable from top-level classroom training. Labwork subjects intend to reflect the most recent advances in research in all areas of modern optics, and in state-of-the-art optical technologies.
The course provides opportunities to perform top-level labwork in instrumental optics (spatial light modulators, phase-shifting interferometer, etc.), optical telecommunications (erbium-doped fibre amplifiers, 10 Gb/s digital transmission), and quantum physics (source of entangled photons, saturated absorption),

**Syllabus**

- **Sensing and imaging with light:**

*Speckle - Roughness and diffraction* (Visual observations and review of the general properties of speckle - Study of the speckle pattern with a CCD camera - Speckle in the image of a scattering object).
*Measurement of object deformations by Speckle Interferometry* (DSPI or Digital Speckle Pattern Interferometry; Study of the properties of the speckle pattern - Speckle interferometry : Study of the phase of the speckle grains - Study of the object deformation).
*Spatial Light Modulators (SLM)* (use of a SLM for intensity or phase modulation).
*Homodyne / Heterodyne sensors*

- **Optical fibers & telecommunications:**

*Slow and fast light regime in nonlinear fiber optics* (The relationship between the change in the optical transmission and the group velocity is investigated in a silica optical fiber by exploiting the very narrow spectral resonance related to the Stimulated Brillouin Scattering (SBS) – Characterization of the optical amplification based on SBS configuration – Experimental study of a tunable optical line delay. )
*Fiber optic gyroscope* (Experimental study of the Sagnac effect)
*Noise in a fiber optical amplifier*
*Dispersion in an optical fiber*

- **Quantum Photonics: (For students who have not followed Optics Labwork 1 )**

*Entangled photons, Hong-Ou-Mandel effect, and Bell inequality* (use of single-photon-counter Modules, counters and coincidence detector. Photon pairs are obtained by spontaneous parametric conversion and, after adjustment of the EPR state, the photon coalescence or a violation of a Bell inequality can be observed).
*Saturated absorption* (Protocol of major interest in atomic physics in order to accurately lock the wavelength of a laser source).
*Second-harmonic generation in nonlinear crystals* (Principle of the second harmonic generation -SHG- effect in 2nd order nonlinear crystals).

**On completion of the course students should be able to:**
Handle experimental techniques and protocols essential in modern experimental physics.

**Textbooks/bibliography:**
http://lense.institutoptique.fr/3am2seq3/

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|---|---|---|
| Course code: | **Quantum communication** | Semester 1 |
| Contributes to: | M2 QLMN – Track “Light and Matter” | |

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|---|---|---|
| **Course directors:**<br>**Co-teachers :** | Isabelle Zaquine (Télécom ParisTech, LTCI) | |
| **Volume:** | CM 14h - TD 7h | **3 ects** |
| **Assessment:** | Multiple Choice Questions test, oral presentation of a research paper | |
| **Language of tuition:** | English or French | |

**Course Objectives:**

Give the state of the art in quantum communications towards the quantum internet

- components and their performance
- examples of protocols
- experimental implementations
- the major challenges of the domain

**Course prerequisites:**

Basics electromagnetism, quantum physics, quantum optics (field quantization)

**Syllabus**

Useful quantum physics notions, entangled photon pair sources and single photon detectors, teleportation, entanglement swapping, cryptography, quantum key distribution systems, device independent security.

**On completion of the course students should be able to:**

- explain how fundamental principles of quantum physics can be used to guarantee the security of communications
- list the requirements of a quantum network (ressources, performance)
- assess the performance of the major components used in quantum communications: sources, detectors, memories
- assess the performance of a communication protocol
- identify some major flaws in a quantum communication system design
- contribute to the design of new quantum communication experiments
- contribute to the development of new quantum information protocols

**Textbooks/bibliography:**

There is no comprehensive book on this subject.

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|---|---|---|
| Course code: | **Recent Experiments in Quantum Information** | Semester 1 |
| Contributes to: | M2 Quantum, Light, Materials and Nano Sciences (QLMN) - | |

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|---|---|---|
| Course director:<br>Course teachers : | J.-P. Hermier (UVSQ)<br>J.-P. Hermier (UVSQ), Y. Dumont (UVSQ), S. Buil (UVSQ), A. Delteil (CNRS) | |
| Volume:<br>Period: | 27 Hours | **3 ects** |
| Assessment: | | |
| Language of tuition: | English | |

**Course Objectives:**

1. Analyze recent experiments in the field of nanophysics and quantum information.
2. Methodology: document analysis (general structure of an article, detailed analysis, overview).
3. Provide an overview of the scientific publishing field.
4. Enlighten and illustrate concepts addressed in other courses through articles.

Various systems (NV, SiV centers, QDs, atomic physics). Various concepts and their physical implementation: coherence, entangled states, fidelity, Bloch sphere, logic gates, quantum sensing. Progressivity: from the simplest to complex protocols.

**Course prerequisites:**

General concepts in nanophysics, nanophotonics and a first approach in quantum information processing. Key concepts for each paper will be shortly presented at the beginning of each session.

**Syllabus**

1. Operations on single qubits: coherence, one-qubit gates (Bloch sphere, fidelity), initialization and output.
2. Two qubit operations and protocols: two qubit gates, remote entanglement, teleportation, quantum sensing.

**On completion of the course students should be able to:**

- Analyze a scientific paper in detail.
- Identify quickly the key points of a publication.

**Textbooks/bibliography:**

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|---|---|---|
| Course code: | **Technologies quantiques: communication, calcul et capteurs** | Semester 1 |
| Contributes to: | M2 Quantum, Light, Materials and Nano Sciences (QLMN) - | |

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|---|---|---|
| Course director:<br>Course teachers : | B. Valiron / T. Antoni | |
| Volume:<br>Period: | 27 Hours | **3 ects** |
| Assessment: | Différente suivant chacune des études de cas, elle seront annoncée par les intervenant lors de chacune de leurs premières séances. | |
| Language of tuition: | English | |

**Course Objectives:**

Le but de ce module est de présenter trois axes principaux identifiés à la fois comme critiques et prometteurs par la Commission Européennes dans le cadre de la seconde révolution quantique. Actuellement en train de sortir des laboratoires les retombées grand public sont attendues à 5-15 ans. l'enseignement se fera sous forme d'une étude de cas en partant des concepts physiques mis à jeu pour aboutir au dimensionnement d'un système permettant d'adresser un enjeu concret.

**Course prerequisites:**

**Syllabus**

Cours sous forme d'étude de cas quantiques :

3. Communication et cryptographie
4. Ordinateur et calcul
5. Capteurs

**On completion of the course students should be able to:**

Connaissance des principales technologies quantiques actuelles et de leurs applications, ainsi que des rudiments de recherche et développement.
(C1.2) Identifier, formuler et analyser un problème dans ses dimensions scientifiques, économiques et humaines.
(C1.3) Utiliser et développer les modèles adaptés, choisir la bonne échelle de modélisation et les hypothèses simplificatrices pertinentes pour traiter le problème.
(C1.4) Résoudre le problème avec une pratique de l'approximation, de la simulation et de l'expérimentation.
(C1.5) Spécifier, concevoir, réaliser et valider tout ou partie d'un système complexe.
(C2.2) Maîtriser les compétences d'un des métiers de base de l'ingénieur (au niveau junior).

**Textbooks/bibliography:**

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|---|---|---|
| Course code: | **Near Field Microscopy** | Semester 1 |
| Contributes to: | M2 QLMN – Track “Light and Matter” | |

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| **Course director:**<br>**Co-teachers :** | Yannick De Wilde (Institut Langevin, CNRS - ESPCI Paris) and Samuel Grésillon (Institut Langevin, SU)<br>Ludovic Douillard (CEA) | |
| **Volume:** | CM: 24 Hours | **3 ects** |
| **Assessment:** | Oral exam | |
| **Language of tuition:** | English or French | |

**Course Objectives:**

The purpose of the course is to provide a detailed description of scanning probe microscopes and electron microscopes, which are the main instruments required to perform nanoscale imaging of various physical properties, to investigate the world of nanoscience and nanotechnology both in academic and industrial research laboratories. The course describes the instruments and the basic principles on which they rely, and explains their modes of operation with illustrative examples.

**Course prerequisites:**

A general background in physics is required to follow the course, mostly oriented towards experimental aspects.

**Syllabus**

- Atomic force microscopy (AFM).
- Scanning tunnelling microscopy (STM) - Scanning electron microscopy (SEM)
- Diffraction limit and theoretical concepts of near-field optics.
- Near-field scanning optical microscopy (NSOM) I : near-field probes.
- Near-field scanning optical microscopy (NSOM) II : active near-field microscopy.
- Near-field scanning optical microscopy (NSOM) III : applications and new trends - Visit of near-field microscopy installations.
- Probing the electromagnetic near field with electrons.

**On completion of the course students should be able to:**

At the end of the course, the students should have acquired a deep understanding and feel ready to use without apprehension, any of the near-field microscopes described in the course. The latter are the roots of the majority of imaging instruments used in nanoscience, which only differ according to the physical quantities which they probe.

**Textbooks/bibliography:**

- « *Les nouvelles Microscopies – A la découverte du nanomonde* », L. Aigouy, Y. De Wilde, Ch. Frétigny, EDITIONS BELIN –COLLECTION ECHELLES (2006).
- « *Principles of Nano-Optics* », L. Novotny and B. Hecht, Cambridge University Press (2006).
- « *Near Field Microscopy and Near Field Optics* », D. Courjon, Imperial College Press (2003) (existe aussi en Français).

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|---|---|---|
| Course code: | **Technologie des Lasers** | Semester 1 |
| Contributes to: | M2 QLMN – Track “Light and Matter” | |

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| **Enseignants** | **Enseignants en charge du cours** : Xavier DELEN (Institut d'Optique Graduate School, Palaiseau) | |
| **Volume horaire** | 24h | **3 ECTS** |
| **Modalités d’évaluation** | Présentation orale en binôme à partir d’articles scientifiques | |
| **Langage** | Français (avec la plupart des transparents en anglais) | |

**Objectifs du cours :**
L’objectif de ce cours est de présenter un état de l’art des différents types de systèmes lasers, continus ou impulsionnels (jusqu’aux lasers femtoseconde) émettant de l’ultraviolet à l’infrarouge. On insistera sur les différentes technologies mises en place récemment en s’appuyant sur des exemples concrets de lasers (souvent commerciaux). On étudiera les solutions technologiques innovantes de lasers à solides pompés par diode récemment mises en place pour améliorer ces performances. Pour chaque type de lasers, des exemples d’applications de ces sources seront présentés. Les techniques de caractérisation spatiale et temporelle sont présentées.

**Pré-requis :** Cours en Physique des Lasers, Lasers à Semi-Conducteurs, Optique Non Linéaire, Polarisation, Acousto-optique, Electro-optique

**Contenu du cours (*copie des transparents distribués*):**

- **Rappel historique, différents types de lasers, marché des lasers, lasers à gaz**
- **Diodes laser de puissance** (rappels sur le fonctionnement des diodes, diodes mono-émetteur, barrettes de diodes laser, amélioration de la brillance)
- **Lasers solides pompés par lampes**
- **Lasers solides pompés par diodes de puissance** (avantages par rapport au pompage par lampes, propriétés des cristaux laser, pompage longitudinal, pompage transverse, lasers à fibre, lasers à semiconducteur pompé optiquement )
- **Conversion de fréquence par effets non linéaires** (propriétés des cristaux non linéaires, oscillateurs paramétriques optiques, matériaux à quasi-accord de phase, lasers solides visibles)
- **Lasers à impulsions ultra-courtes** (différentes techniques de verrouillage de modes, oscillateurs femtosecondes à saphir dopé au titane, amplification à dérive de fréquence, présentation des chaînes laser femtosecondes commerciales basse et haute cadence, accordabilité par effet paramétrique optique, nouveaux lasers femtosecondes pompés directement par diodes)
- **Caractérisation spatiale et temporelle d'un faisceau laser** (analyse de surface d’onde, M2, correction active, autocorrelation, FROG, contrôle actif de la phase… **)**
- **Applications des lasers à impulsions ultra-courtes** (spectroscopie non linéaire résolue en temps, microscopie de fluorescence, generation d’impulsions attosecondes, micro-usinage athermique, chirurgie refractive de l’oeil).

**Compétences attendues à la fin de l’UE :**

- comprendre les solutions techniques mises en œuvre dans un système laser (régime continu ou impulsionnel)
- analyse d'articles scientifiques sur la technologie laser
- faire une analyse critique des choix scientifiques et techniques mis en œuvre dans les systèmes laser
- définir une architecture de système laser pour atteindre une bande de longueur d'onde spécifique, une puissance moyenne ou une énergie, une durée d'impulsion
- comprendre la fiche technique d’un système laser
- choisir le système laser le plus approprié pour une application spécifique
- faire une revue scientifique et technique d'une technologie laser spécifique.

**Bibliographie :**

“Lasers” A Siegman, Stanford University“, (University Science Books, (1986) ISBN 978-0-935702-11-8,
“Solid-State lasers Engineering” W. Koechner, Springer 6th Edition ISBN-10: 038729094X ISBN-13: 978-0387290942
“Solid-State lasers” M. Bass, W. Koechner, Springer ISBN10 : 0-387-95590-9 ISBN13 : 978-0-387-95590-2
“High Power Laser Handbook”, H. Injeyan, G.D. Goodno, The McGraw-Hill Companies, Inc, ISBN: 978-0-07-160902-9
“Ultrashort pulses and applications“ A Galvanauskas Marcel Dekker, Inc. Ed. New York (2002)
“Ultrafast Optics”, A. Weiner, Wiley Series in Pure and Applied Optics, ISBN : 978-0-471-41539-8
Web-site : Encyclopedia of Laser Physics and Technology http://www.rp-photonics.com
"The principle of nonlinear optics", Y.R. Shen, Wiley, (1984)
"Nonlinear Optics", RW Boyd, C Braun, Academic, San Diego, Calif, (2003)

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|---|---|---|
| Course code: | **Biophotonics** | Semester 1 |
| Contributes to: | M2 QLMN – Track "Light and Matter" | |

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| **Course director:**<br>**Course teachers :** | A. Dubois (Lab. Charles Fabry, IOGS)<br>E. Beaurepaire (Lab. d'Optique et Biosciences, Ecole Polytechnique), H. Benisty (Lab. Charles Fabry, IOGS), C. Bouzigues (Lab. d'Optique et Biosciences, Ecole Polytechnique), A. Dubois (Lab. Charles Fabry, IOGS), N. Westbrook (Lab. Charles Fabry, IOGS) | |
| **Volume:** | 24 Hours<br>CM : 21h TP/ visits : 3h | **3 ects** |
| **Assessment:** | Written exam | |
| **Language of tuition:** | English or French | |

**Course Objectives:**
To give insights into modern research trends in biophotonics. To provide in particular an overview of the various optical techniques available for biomedical imaging and detection, giving their characteristics and highlighting their advantages and drawbacks.

**Course prerequisites:** Basics of ray optics, wave optics, electromagnetism, nonlinear optics and quantum mechanics. Basics of biochemistry. Basics of DNA and proteins.

**Syllabus**

**- INTRODUCTION TO OPTICAL IMAGING OF BIOLOGICAL MEDIA**

**- INTRODUCTION TO CELL BIOLOGY**
Cellular components, DNA, RNA, proteins.

**- OPTICAL MICROSCOPY**
Fluorescence microscopy, confocal microscopy. Full-field imaging techniques. Organic/inorganic fluorophores.

**- FLUORESCENCE TECHNIQUES**
Single-molecule tracking, Fluorescence Recovery After Photobleaching (FRAP), Fluorescence Correlation and Cross-Correlation (FCS, FCCS), Fluorescence lifetime imaging (FLIM), Fluorescence Resonant Energy Transfer (FRET).

**- SUPER-RESOLUTION IMAGING**
Total Internal Reflection Fluorescence microscopy (TIRF), 4π microscopy, Stimulated Emission Depletion microscopy (STED), Stochastic Optical Reconstruction Microscopy (STORM), PhotoActivated Localization Microscopy (PALM).

**- OPTICAL TWEEZERS**
Single molecule manipulation.

**- DNA and PROTEIN MICRO-ARRAYS**
Readout techniques: fluorescence and Surface Plasmon Resonance, Biochip specifications and realizations, Data processing and interpretation.

**- NON-LINEAR MICROSCOPY**
Two-photon excitation fluorescence microscopy,
Harmonic generation microscopy;
Coherent Anti-Stokes Raman Scattering (CARS) microscopy.

**- OPTICAL COHERENCE TOMOGRAPHY**
Time-domain / frequency-domain OCT. Applications.

**On completion of the course students should be able to:** have knowledge of most optical techniques available for imaging and detection in the fields of biology and medicine. The general principles and typical performance of theses techniques should be known.

**Textbooks/bibliography:**
- P. N. Prasad, *Introduction to Biophotonics*, Wiley, 2003
- J. R. Lakowicz, *Principles of fluorescence spectroscopy*, 3rd edition, Springer, 2006
- J. Mertz, *Introduction to optical microscopy*, Roberts & Co. Publishers, 2009
- M. Müller, *Introduction to Confocal Fluorescence Microscopy*, SPIE Press, 2006
- R. Rigler, H. Vogel (eds.), *Single molecules and Nanotechnology*, Springer, 2008
- P. Selvin, T. Ha (eds.), *Single-Molecule Techniques: A Laboratory Manual* , CSH Lab. Press, 2008
- P. R. Selvin, *Methods in Enzymology*, Vol. 124, Academic Press (1995), p. 300
- W. Drexler, J.G. Fujimoto (eds.), *Optical Coherence Tomography, Technology and Applications,* Springer, 2008

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|---|---|---|
| Course code: | **Fonctions et intégration photonique** | Semester 1 |
| Contributes to: | M2 QLMN – Track “Light and Matter” | |

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|---|---|---|
| **Responsable:**<br>**Enseignants:** | Henri BENISTY (IOGS/U-PSUD)<br>Henri BENISTY (IOGS) ; Mme Béatrice Dagens (IEF,CNRS), M. Guang Hua DUAN (III-V Lab), M. Daniel DOLFI (Thales TRT) | |
| **Volume horaire:** | 24h ; CM 24h + soutien personnalisé sur analyse d'articles | **3 ects** |
| **Modalités d’évaluation:** | Examen à base d'analyse d'un article avec interrogation orale sur son contenu et le contenu du cours en relation avec cet article. | |
| **Langue:** | Français | |

**Objectifs du cours:**
Expliciter les principes de fonctionnement et les technologies des dispositifs photoniques semiconducteurs, dans une perspective d’intégration. On s’appuiera d’abord sur un cas mature, les télécoms optiques pour les réseaux actuels puis on verra les tendances émergentes prochainement déployées. On donne dans la fin du cours les méthodes de traitement du signal par voie électro-optique et acousto-optique, telles qu’elles sont utilisées au-delà des télécom en photonique micro-onde et dans les lidars.

**Pré-requis:** Diode laser de base (Fabry-Perot), milieux à gain et électro-optiques, bases des télécoms optiques (fibres, modes, débit).
→ Ouvrage "Fundamentals of Photonics" de B.A. Saleh & M.C. Teich (Wiley) (2nd Ed : 2007).

**Contenu du cours**

**1) Couplages d’ondes, dispositifs emblématiques (6h, H. Benisty) :**
Rappel des descriptions de couplage d’onde et de semi-conducteur. Application de ces concept au travers de dispositifs emblématiques (QW laser,DFB, VCSEL,QD laser).

**2) le cycle performance – technologie des composants télécoms (Béatrice Dagens, IEF)**
- Détail des composants individuels puis intégrés: Nous considérerons d’abord en détail le cas « élémentaire » du laser à semi-conducteur, pour introduire progressivement les principes physiques sous-jacents à l’ensemble des composants optoélectroniques, leur technologie de fabrication, les principes et les degrés de liberté de leur conception. Cela nous conduira jusqu’à l’intégration des composants en circuits photoniques et les compromise supplémentaires sur la conception liés à l’ensemble de la technologie. Nous aborderons également les autres technologies de composants optoélectroniques (verre, SOI, LiNbO3), et nous évoquerons les circuits photoniques développés pour des applications non télécom (bioplasmonique). Ces bases étant acquises, nous pourrons approfondir la physique du fonctionnement et certains principes de caractérisation des composants phares de l’optoélectronique évoqués au début du cours.

**3) Composants télécom et datacom : tendances émergentes : (Guang-Hua DUAN, 3-5Lab)**
- On traitera dans cette partie plusieurs tendances observées ces dernières années dans le domaine de télécommunications et de data communication : le multiplexage et le routage en longueur d’onde, les nouveaux formats de modulation et l’intégration photonique sur silicium. Dans la partie multiplexage et routage en longueur d’onde l’accent sera mis sur les sources accordables en longueurs d’onde et la manipulation de la longueur d’onde (filtrage, routage, translation etc.).
- Sur les nouveaux formats de modulation, on détaillera les circuits photoniques utilisant par exemple une combinaison de plusieurs interféromètres Mach-Zehnder. Sur l’intégration photonique sur silicium, on expliquera les différentes briques de base : laser, modulateur, photo-détecteurs, guides passifs sur silicium, etc. On montera plusieurs exemples d’intégration pour les applications en télécommunications et en "data communication".

**4) Traitement du signal électro- et acousto-optique, applications micro-ondes et lidar (D.Dolfi -TRT Thales)**

- Phénomènes électro et acousto-optiques et applications : biréfringence induite dans les cristaux et les céramiques, opération en espace libre et en guidage de modes, modulateurs pour les télécom, commutation et balayage électro et acousto-optique de faisceaux lasers.
- Propriétés optiques et électro-optiques des cristaux liquides : phases de cristal liquide, tenseurs optiques et électro-optiques, technologies des cellules de cristaux liquides.
- Applications :afficheurs, vannes à lumières, optique non linéaire Comparaisons avec d'autres technologies, application au mélange d'onde dans les matériaux, holographie en volume – matériaux : photoréfractifs, à gain, Diffusion Brillouin stimulée ; application du mélange d'onde à l'amplification d'image et à la conjugaison optique. Applications au traitement du signal, au contrôle de faisceau laser, aux compensations d'effets thermiques.
- Liaisons électro-optiques, des télécoms aux radars. Principales caractéristique d'une liaison (gain, figure de bruit, linéarité, gamme dynamique) :des exigences systèmes à la physique du composant ; Applications au traitement optoélectronique de signaux radars (antennes intelligentes [phased array antennae], filtrage agile, corrélation, analyse spectrale, oscillateurs, horloges ultra-précises) ; Génération photonique et détection de signaux millimétriques (fréquence> micro-onde) et THz ; Principes de base des systèmes lidars.

**Compétences attendues à la fin de l'UE:** A l'issue du cours, les élèves peuvent identifier au sein des dispositifs de l'optique intégrée courants à l'état de l'art les différentes briques de base, et dans chaque brique (confinement, réseau périodiques, boites quantiques), de comprendre pourquoi la valeur en proposée des paramètres a été au final adoptée.

**Bibliographie:**

- *The principles of nonlinear optics*, Y.R. Shen (Wiley-Interscience)
- *Wave Mechanics applied to semiconductor heterostructures*, G.Bastard (Springer) –
- *Quantum semiconductor Structures : Fundamentals and applications*, C. Weisbuch & B. Vinter (Acadeic Press)
- H. C. Casey, Jr. and M. B. Panish, « *Heterostructure Lasers* », Academic Press, 1978 –
- G. H. B. Thomson, « *Physics of semiconductor Laser Devices* », John Wiley, 1980
- Govind P. Agrawal, Niloy K. Dutta, « *Semiconductor Lasers* », Van Nostrand Reinhold, 2nd ed. 1993,
- Philippe Brosson, « *Semiconductor lasers and integrated devices* », Les Houches, summer school on « lasers and applications », June 2000.

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| Course code: | **Optique Adaptative** | Semester 1 |
| Contributes to: | M2 QLMN – Track "Light and Matter" | |

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| **Responsable:**<br>**Enseignants:** | Caroline Kulcsár (IOGS)<br>Jean-Marc Conan (ONERA), C. Kulcsár (IOGS) | |
| **Volume horaire:** | 24h | **3 ects** |
| **Modalités d'évaluation:** | QCM | |
| **Langue:** | Français | |

**Objectifs du cours:**
Le cours traite de la propagation optique à travers la turbulence, de l'optique adaptative et de l'interférométrie multi-pupille : des concepts physiques aux règles de dimensionnement système, en passant par les notions associées de traitement de signal/images et d'automatique. Ces principes sont appliqués aux trois domaines suivants :

- imagerie haute résolution en astronomie exploitant un ou plusieurs télescopes
- télécommunications optiques sol-espace à très haut débit
- biomédical : ophtalmologie et microscopie

**Plan détaillé :**

- COURS 1 & 2 (J.-M. Conan) : Propagation et imagerie à travers la turbulence
  - origine physique de la turbulence
  - propagation optique : effets de phase et de scintillation
  - pourquoi les planètes ne scintillent pas (ou très peu) ?
  - notion d'anisoplanétisme et de temps caractéristique d'évolution
  - formation d'image : courtes et longues poses

- COUR 3 (G. Rousset) : Imagerie de speckle & Interférométrie longue base multi-télescope
  - restauration d'images par techniques speckle
  - déconvolution par analyse de front d'onde
  - interférométrie longue base multi-télescope
    - interféromètre stellaire de Michelson en présence de turbulence
    - estimation de l'objet à partir des mesures interférométriques
    - exemple de grands interféromètres

- COURS 4 (G. Rousset) : Analyse de front d'onde
  - différentes stratégies d'analyse de front d'onde
  - bruit d'analyse
  - reconstruction sur une base modale (polynômes de Zernike)

- COURS 5 (J.-M. Conan) : Optique adaptative
  - principe & composants
  - règles de dimensionnement et budget d'erreur
  - application à l'imagerie haute résolution en astronomie
    (optiques adaptatives pour télescopes de 8 à 40 m, étoile laser, imagerie grand champ...)

- COURS 6 (C. Kulcsár) : Commande des systèmes d'optique adaptative
  - l'optique adaptative : une boucle de commande avec retard
  - approche classique (matrice d'interaction, commande intégrateur)
  - commande optimale (formulation d'état, filtre de Kalman, commande LQG)
  - exemple de résultats expérimentaux

- COURS 7 (J.-M. Conan) : Optique adaptative pour les télécoms sol-espace et le biomédical
  - télécommunications optiques sol-espace à très haut débit
    - effet de la turbulence sur couplage dans une fibre monomode
    - notion de réciprocité et d'anisoplanétisme de pointage en avant
    - les enjeux de l'optique adaptative pour les liens montants et descendants
  - applications biomédicales
    - optique adaptative pour l'imagerie et la chirurgie en ophtalmologie
    - optique adaptative en microscopie

**Compétences attendues à la fin de l'UE:**

- Acquérir les notions fondamentales sur les perturbations limitant les performances des systèmes optiques dans des milieux aberrants (turbulence atmosphérique, biologie)
- Comprendre les techniques optiques et numériques permettant de corriger ces effets pour s'approcher de la performance ultime donnée par la limite de diffraction (imagerie à haute résolution angulaire, liens télécoms à très haut débit, chirurgie laser à haute précision...)

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| Course code: | **Optique de l'extrême** | Semester 1 |
| Contributes to: | M2 QLMN – Track “Light and Matter” | |

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| **Responsable:**<br>**Enseignants:** | Charles Bourassin-Bouchet | |
| **Volume horaire:** | 24h | **3 ects** |
| **Modalités d’évaluation:** | Examen oral | |
| **Langue:** | Français | |

**Objectifs du cours:**

L’objectif de ce module est de faire découvrir aux étudiants la physique et l’optique aux très courtes longueurs d'onde (domaine spectral de l'extrême ultraviolet aux rayons X) et aux très courtes durées (femtosecondes et attosecondes). Après quelques rappels sur les impulsions ultrabrèves, on s'intéressera aux sources à génération d’harmoniques d’ordre élevé pour la génération d'impulsions attosecondes, aux lasers à électrons libres et aux composants optiques utilisés sur ces sources. Nous terminerons en présentant quelques applications du rayonnement XUV ultrabref en physique fondamentale.

Ce domaine est en plein essor au niveau local (Synchrotron SOLEIL, station laser X à Paris Sud, installation Attolab et laser Pétawatt Appolon à l’Orme des Merisiers) et également au niveau international (installation ELI en Europe, lasers à électrons libres X-FEL aux USA et en Europe)…

**Pré-requis:** physique et optique générale.

**Contenu du cours**

- Introduction
- Notions d'optique ultrabrève
- Génération d'harmoniques d'ordre élevé et impulsions attosecondes
- Synchrotrons et Lasers à électrons libres
- Accélération de particules par laser - Visite du Laboratoire d'Optique Appliquée
- Interaction XUV-matière, composants optiques
- Applications des impulsions XUV ultrabrèves

**Compétences attendues à la fin de l’UE:**
Avoir une compréhension générale de la physique et de l'optique aux courtes longueurs d'onde et aux temps ultrabrefs.

**Bibliographie:**
David Attwood, *Soft X-Rays and Extreme Ultraviolet Radiation* (Cambridge University Press)
Jens Als-Nielsen and Des McMorrow, *Elements of Modern X-ray Physics* (Wiley)

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| Course code: | **Impulsions optiques ultra-brèves** | Semester 1 |
| Contributes to: | M2 QLMN – Track "Light and Matter" | |

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| **Responsable:**<br>**Enseignants:** | Pierre Mahou (Laboratoire d'Optique et Biosciences, CNRS-Ecole Polytechnique)<br>Louis Daniault (Laboratoire d'Optique Appliquée, Ecole Polytechnique)<br>Pascal Salières (Laboratoire Interactions, Dynamiques et Lasers, CEA-Saclay) | |
| **Volume horaire:** | 24H ( CM 13H30 - TD 7H30 – Visite 3h00) | **3 ects** |
| **Modalités d'évaluation:** | Examen oral | |
| **Langue:** | Français | |

**Objectifs du cours:**

Les objectifs de ce cours sont de présenter d'une part les propriétés remarquables des impulsions lasers ultrabrèves (sub-picoseconde) et les principes de leur génération, et d'autre part les applications de plus en plus nombreuses dans des domaines très variés : spectroscopie, microscopie, métrologie, nouveaux types de sources de rayonnement, etc…Ce cours introduit les notions et outils nécessaires pour comprendre les phénomènes mis en jeu, ainsi que les techniques expérimentales permettant d'engendrer, amplifier, caractériser et manipuler les impulsions dites « femtosecondes ».

**Pré-requis:**
Optique linéaire et non-linéaire, Lasers, Optique de Fourier.

**Contenu du cours**

1. Présentation. Propagation d'une impulsion brève. Etirement et compression. Façonnage temporel.
2. Génération, amplification. Caractérisation temporelle, mesure de phase spectrale.
3. Phénomènes non-linéaires : mélange de fréquence, effet Kerr, effet Raman, génération de continuum spectral…
4. Applications : spectroscopie ultrarapide, contrôle cohérent, spectroscopie multidimensionnelle, métrologie des fréquences.
5. Applications : photoablation et micro-usinage, imagerie (microscopie, nanoscopie), génération de rayons X.
6. Visite des installations du Laboratoire d'Optique et Biosciences et du Laboratoire d'Optique Appliquée en rapport avec le cours
7. Génération d'harmoniques d'ordre élevé.
8. Génération et applications d'impulsions attosecondes ($10^{-18}$ s).

**Compétences attendues à la fin de l'UE:**
A l'issue du cours les étudiants maitrisent les outils nécessaires à la modélisation et à l'utilisation des impulsions courtes, les relations entre durée et spectre, la notion de phase spectrale. Ils connaissent le principe de génération des impulsions brèves et les techniques de caractérisation telles que le FROG ou le SPIDER. Ils ont étudié les applications les plus courantes, et plus en détail la génération d'impulsions attosecondes.

**Bibliographie:**

*Femtosecond Laser Pulses, Principles and experiments*, Claude Rulliere, Ed. Springer, Advanced Texts in Physics, 2005
*The Elements of Non-linear Optics*, Paul N. Butcher, David Cotter, Cambridge studies in Modern Optics 9, 1991

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| Course code: | **Plasma Physics** | Semester 1 |
| Contributes to: | M2 QLMN – Track "Light and Matter" | |

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| **Course director:** | Timothée Nicolas (CPHT, CNRS) | |
| **Volume:** | 27 hours | **3 ects** |
| **Assessment:** | oral or written examination (depending on the number of students) | |
| **Language of tuition:** | French | |

**Course Objectives:**
To give an introduction to plasma physics. A particular attention will be given to plasmas created by lasers, as the Saclay area hosts two of the most powerful and energetic lasers in the world, and as the corresponding local scientific community is recognized as being at the top international level.

**Course prerequisites:**
Classical electrodynamics (e.g., Jackson's text book)

**Syllabus**
1. Introduction. Interest for plasmas; plasmas in nature and in laboratories; plasmas for thermonuclear controlled fusion; Saha equilibrium; Fermi temperature and degenerated plasmas; classification of plasmas.
2. Basic notions. Debye length; coupling parameter; electron and ion plasma frequencies; binary collisions and coulomb logarithm; collisional mean free path.
3. Fluid description and kinetic theory. Distribution functions; mean fields and Vlasov-Maxwell equations; collisional kinetic equation; fluid quantities and fluid equations; closure of fluid equations.
4. Fluid theory of plasma waves. Dispersion relation, phase velocity, group velocity; electrostatic waves in cold plasmas; thermal corrections; ion acoustic waves; electromagnetic waves; propagation in inhomogeneous plasmas; BKW approximation.
5. Kinetic theory of electron plasma waves. Landau damping. Laplace transform and complex analysis.
6. Trapping of particles in longitudinal waves. Motion of a particle in a finite amplitude wave; circulating and trapped particles; separatrix; wave-particle interaction.
7. Nonlinear waves in plasmas. Ponderomotive force; parametric instabilities of laser beams in plasmas.

**On completion of the course students should be able to:**
understand the main characteristics of plasma physics, its specificity with regards to other fields of physics; distinguish the main waves propagating in a plasma, and caculate their dispersion relation and their phase velocity; have an insight in the dynamical and nonlinear aspects of plasma physics.

**Textbooks/bibliography:**
P. Mora, Plasmas créés par laser, généralités et applications choisies, EDP Sciences (2021)
J.-M. Rax, Physique des plasmas, Dunod 2005 (in french)

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| Course code: | **Structure Moléculaire et Transition Optique** | Semester 1 |
| Contributes to: | M2 QLMN – Track “Light and Matter” | |

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| Course director:<br>Course teachers ; | Niloufar Shafizadeh( DR-CNRS-ISMO)<br>Jean-Hugues Fillion (Professeur UPMC-LERMA), Niloufar Shafizadeh(ISMO) | |
| Volume:<br>Period: | 27 heures | **3 ects** |
| Assessment: | Examen écrit | |
| Language of tuition: | French | |

**Course Objectives** Le but de ce cours est d'enseigner aux étudiants comment analyser et extraire des informations d'un spectre moléculaire. Les spectres moléculaires apportent des informations fondamentales sur la structure et la géométrie des molécules, leurs surfaces d'énergie potentielle et, les couplages entre les différents moments angulaires internes. De nos jours, la spectroscopie moléculaire est un outil direct et puissant pour déterminer la composition et les propriétés physiques (par exemple la température) de milieux inaccessibles tels que les atmosphères planétaires, les mélasses de molécules froides ou le cœur d'un moteur ou d'une fusée
On insistera sur les aspects de symétries et parités liées aux structures moléculaires.
*Les modèles qui décrivent les fonctions d'onde électroniques, vibrationnelles et rotationnelles des molécules et leurs symétries .
*Les approximations qui permettent de décrire le mouvement nucléaire dans les molécules (vibration et rotation).
*Le couplage entre le moment cinétique orbital et le moment cinétique rotationnel.
*Les règles de sélection qui permettent l'interaction entre le rayonnement et les molécules.
Cette option est une approche directe pour décrire la structure électronique de molécules isolées.

**Course prerequisites:** Eléments de mécanique quantique

**Course Corequisites** : none

**Syllabus**
**Chapitre I –**Introduction à la théorie de groupe
**Chapitre II-** Les bases pour comprendre la structure moléculaire
**Chapitre III-** Structure électronique d’une molécule diatomique
**Chapitre IV-** La molécule avec spin électronique -Interaction spin-orbite
**Chapitre V-** Structure vibrationnelle et rotationnelle d’une molécule diatomique
**Chapitre VI-** Interaction molécule- rayonnement
**Chapitre VII-** Moment de transition pour une transition dipolaire électrique à un photon et puis plusieurs photons .

On completion of the course students should be able to:
Les étudiants seront capables d'analyser un spectre moléculaire et d'en extraire des informations sur la structure moléculaire, la géométrie et les niveaux d'énergie du système.

Textbooks/bibliography:
*** Gerhard Herzberg** *Molecular Spectra and Molecular Structure volume 1,2,3*
***Hollas** *Spectroscopie* Dunod Paris 1998
***Emile Biémont** *Spectroscopie Moléculaire* édition de boeck 2008
***Hélène Lefevre-Brion and Robert Field** *Spectra and dynamics of diatomic molecules* Elsevier Academic Press 2004
***Edmonds** *Angular Momentum in Quantum Mechanics* (Princeton University Press Princeton 1974
***R.N Zare** *Angular Momentum Undrestanding Spatiale Aspects in Chemistry and Physics* Wiley –Interscience publication 1987
***Condon and Shortley** *The Theory of Atomic Spectra*
*Jeffrey Steinfeld *Molecules And Radiation: An Introduction To Modern Molecular Spectroscopy*

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| Course code: | **Dynamique réactionnelle photo-induite : de la molécule isolée aux systèmes complexes** | Semester 2 |
| Contributes to: | M2 Quantum, Light, Materials and Nano-Sciences / Light and Matter | |

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| **Enseignants:** | Karine STEENKESTE (ISMO, Université Paris-Saclay)<br>Lionel POISSON (ISMO, Université Paris-Saclay)<br>Jérémie CAILLAT (LCPMR, Sorbonne Université) | |
| **Volume horaire:** | CM 24h<br>Visite 3h | **3 ects** |
| **Modalités d'évaluation:** | Discussions avec le jury sur la base d'un thème abordé et tiré au sort<br>(20 min préparation/20 min discussion) | |
| **Langue:** | English or French | |

**Objectifs du cours**

Ce cours vise à faire découvrir les techniques existantes pour le suivi résolu en temps des dynamiques prenant place au sein de systèmes moléculaires. Nous partirons de résultats expérimentaux pour aborder les phénomènes physiques et chimiques qui gouvernent ces dynamiques. Nous explorerons des phénomènes se déroulant à diverses échelles de temps : de l'atto-seconde pour des processus électroniques, femto/picoseconde pour des processus vibrationnels à des échelles de temps jusqu'à la milliseconde pour les processus se déroulant dans les systèmes biologiques ou photovoltaïques.

**Pré-requis**

Connaissances en physique des lasers et spectroscopie.

**Contenu du cours**

1. Dynamique résolue en temps : Techniques Pompe/sonde, conceptualisation, expériences, mécanismes de la relaxation électronique.
2. Spectroscopie résolue en temps à l'échelle atto-seconde : Génération d'impulsions atto-seconde, accès aux dynamiques fondamentales atto-secondes de la chimie, outils théoriques pour l'interprétation des expériences.
3. Application aux complexes biologiques et aux systèmes photovoltaïques.
4. Une visite des installations expérimentales de l'ISMO, dédiées à l'étude de la dynamique photo-induite, sera organisée dans le cadre de ce module.

**Compétences attendues à la fin de l'UE**

Compréhension de la physique qui permet de produire ou de sonder un phénomène dépendant du temps dans un système moléculaire. Connaissance de divers processus de relaxation de l'énergie. Connaissance des méthodes expérimentales dédiées. Connaissances sur l'interaction laser-molécule sous diverses conditions.

**Bibliographie**

H. Zewail, J. Phys. Chem. A 2000, 104, 5660-5694.

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| Course code: | **Ultracold Molecules and Rydberg atoms: Interaction, Dynamics and Control** | Semester 1 |
| Contributes to: | M2 QLMN – Track “Light and Matter” | |

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| Course teachers: | Goulven Quéméner, Patrick Cheinet (Laboratoire Aimé Cotton, CNRS, Université Paris-Saclay) | |
| Volume:<br>Period: | 30 Hours<br>December - February | **3 ects** |
| Assessment: | bibliographic project + oral presentation | |
| Language of tuition: | English (or French, depending on the audience) | |

**Course Objectives:**

- Multipolar expansion in Cartesian and spherical coordinates; application of quantum perturbation theory to calculate long-range interactions; examples of their importance for modern research in ultracold gases
- Theory of ultracold collisions (partial waves). Control of interactions and dynamics with magnetic and electric fields and electromagnetic waves
- Applications to ultracold molecules and Rydberg atoms

**Course prerequisites:**

Quantum mechanics, basics in atomic and molecular physics.

**Syllabus**

**1. An overview on ultracold molecules and Rydberg atoms (3h)** (Goulven Quéméner, Patrick Cheinet)

**2. Long-range interactions between atoms and molecules (6h)** (Patrick Cheinet)
**2.1** Reminder: atomic and molecular quantum numbers
**2.2** Calculation of electrostatic energy between two charge distributions
**2.3** Long-range interactions in ultracold matter

**3. Ultracold molecules collisions with control by fields and waves (12h)** (Goulven Quéméner)
**3.1** Collisions of two molecules: Time-independent Schrödinger equation and generalities
**3.2** Collisions of two molecules: Partial wave expansion and coupled equations
**3.3** Collisions of two molecules: Cross sections and rate coefficients
**3.4** Simple collisional models
**3.5** Magnetic field control of ultracold matter
**3.6** Formation of molecules with electromagnetic waves
**3.7** Electric field control of ultracold matter

**4. Rydberg atoms and their interactions (6h)** (Patrick Cheinet)
**4.1** Recalling basic properties
**4.2** Long distance interactions between Rydberg atoms
**4.3** Circular Rydberg atoms
**4.4** Divalent atoms
**4.5** Towards various applications: quantum simulation, electromagnetic field sensors

**On completion of the course students should be able to:**

- understand how interactions between ultracold molecules or Rydbergs atoms are described
- get a knowledge on the collisional formalism between ultracold molecules
- understand how one can form and control ultracold molecules with fields and electromagnetic waves
- compute various Rydberg atoms properties (AC-DC Stark effect, interactions…)
- get an overview of the field of ultracold molecules and Rydberg atoms, and their applications

**Textbooks/bibliography:**

- M. Lepers, O. Dulieu, "Long-range interactions between ultracold atoms and molecules", in Cold chemistry: Molecular scattering and reactivity near absolute zero, edited by A. Osterwalder, O. Dulieu, The Royal Society of Chemistry (2018), https://arxiv.org/abs/1703.02833
- G. Quéméner, "Ultracold collisions of molecules", in Cold chemistry: Molecular scattering and reactivity near absolute zero, edited by A. Osterwalder, O. Dulieu, The Royal Society of Chemistry (2018), https://arxiv.org/abs/1703.09174
- G. Quéméner, P. S. Julienne, "Ultracold molecules under control!", Chem. Rev. 112, 4949 (2012)
- T. F. Gallagher, “Rydberg atoms” (Cambridge University Press 1994)
- H. A. Bethe and E. E. Salpeter, “Quantum mechanics of one- and two-electron atoms”, Springer 1957
- D. A. Varshalovitch, A. N. Moskalev and V. K. Khersonskii, “Quantum theory of angular momentum”, World Scientific, 1988

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| Course code: | Quantum Sensing | Semester 1 |
| Contributes to: | M2 Quantum, Light, Materials and Nano Sciences (QLMN) - | |

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| Course director:<br>Course teachers : | François Marquier<br>François Marquier, François Treussart, Christoph Westbrook | |
| Volume:<br>Period: | 27 Hours | **3 ects** |
| Assessment: | Oral or written exam depending on the number of students | |
| Language of tuition: | English or French depending on the students’ origin | |

**Course Objectives:**
Understand how quantum states can improve the sensing of properties of different systems. The concepts will be illustrated by examples in physics and biology.

**Course prerequisites:**
Quantum mechanics and basics of light-matter interaction, some familiarity with quantized electromagnetic fields

**Syllabus**
Each time slot is separated into a concept introduction and tutorials, often illustrated by scientific papers. The aim of the course is to highlight classical limits that can be overcome by a quantum approach of the measurements. We will come back on the notion of discrete and continuous quantum bits, and how to use it to measure magnetic fields, orientation of particles, temperature, pH... To this aim we will consider the unique system of negatively charged nitrogen-vacancy centers in diamond, possessing an electron spin resonance that can be detected optically.
We will also discuss the detection of inertial effects (acceleration and rotation) using atom interferometry, and the use of squeezed and other non-classical states to improve the performance of (mostly) optical interferometers, such as gravitational wave detectors.

**On completion of the course students should be able to:**

- Know how to use a quantum state to perform a measurement and get a better signal-to-noise ratio.
- Understand some of the basic scientific papers in this field

**Textbooks/bibliography:**
"Introductory Quantum Optics", C.C. Gerry and P.L. Knight, Cambridge Univ. Press (2005)