2nd Year Master Course (M2)

Laser Optics Matter (LOM)

COURSE CATALOGUE

Academic Year 2016-2017

Master 2 – Laser, Optics, Matter (LOM)
Semester 1 – 2015-2016
Final award : *Master 2 mention Physique, parcours Laser, Optique, Matière*

		Course title	Course Co-ordinator	ects	Hrs	Lang
Electives A : 2 or 3 courses to be taken from A1, A2, A3 (6 or 9 ects)	A1	Laser Physics	M. HANNA	3	33	Eng
	A2	Nonlinear Electromagnetism	N. DUBREUIL / F. HACHE	3	33	Eng
	A3	Quantum dynamics of light-matter interaction	E. CHARRON	3	33	Eng
Electives B : 4 or 3 courses to be taken from B1 to B5 (12 or 9 ects)	B1	Quantum Optics	C. WESTBROOK / A. BROWAEYS	3	30	Eng
		Nanophotonics	H. BENISTY	3	30	Eng
	B2	Optical properties of solids	JS. LAURET	3	33	E/Fr
		Interactions between light and atoms	D. CLEMENT / T. CHANELIERE	3	33	E/Fr
	B3	Mécanique quantique approfondie	D. BENREDJEM / L. PRUVOST	3	27	Fr
		Plasma Physics	P. MORA	3	24	E/Fr
		Non-Equilibrium Statistical Physics	D. GREBENKOV	3	24	E/Fr
	B4	Statistical Optics	D. CLEMENT	3	33	Eng
		Approches statistiques en physique moléculaire	P. PARNEIX	3	24	Fr
		Structure moléculaire et transitions optiques	N. SHAFIZADEH	3	24	Fr
	B5	Optics Labwork	F. BERNARD	3	27	Fr/E
Free electives						
4 electives (4x3ects) to be taken from one of the following sets (12 ects)		Full details about available courses can be found on https://www.universite-paris-saclay.fr/fr/formation/master/m2-laser-optique-matiere#programmes		3		
				30		

Eng: English Only; Fr: French Only; E/Fr: French or English (in English if foreigner students are attending the course)

Course Catalogue : Table of Contents

Course code:	**Laser Physics**	Semester 1
Contributes to:	M2 Laser-Optics-Matter	

Course director: Course teachers :	Marc Hanna (LCF) Fabien Bretenaker (LAC), Frédéric Druon (LCF), Fabien Quéré (CEA)	
Volume: Period:	33 Hours Weeks 37-49 with written examination week 50.	**3 ects**
Assessment:	Final exam / midterm exam	
Language of tuition:	English or French	

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

1. Matter-light interaction; Equations of the single-frequency laser
2. Single frequency laser in steady-state regime
3. Inhomogeneous line broadening
4. Transient and Q-switched operation
5. Noise properties of lasers
6. Mode-locking and ultrashort pulses
7. Optical resonators: ray matrices, Gaussian beams, cavity stability
8. 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

Course code:	**Nonlinear Electromagnetism**	Semester 1
Contributes to:	M2 Laser-Optics-Matter	

Course director: Course teachers :	Nicolas Dubreuil (LCF), François Hache (LOB) Isabelle Zaquine (TPT), Marie-Claire Schanne-Klein (LOB)	
Volume: Period:	33 Hours Weeks 37-49 with written examination week 50.	**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
Brillouin Scattering : spontaneous and stimulated effects
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:
Lecture notes available at http://paristech.iota.u-psud.fr/site.php?id=84
Robert W. Boyd, Nonlinear Optics, 4th Edition, Elsevier Ed
BUTCHER, PAUL N. / COTTER, DAVID, The Elements of Nonlinear Optics , Cambridge University Press.1993.
F. Sanchez, Optique non linéaire, Ellipses, 1999.

Course code:	**Quantum dynamics of light-matter interaction**	Semester 1
Contributes to:	M2 Laser-Optics-Matter	

Course director: Course teachers:	Eric CHARRON	
Volume/Period:	33 Hours / September-December	**3 ECTS**
Assessment:	1 exam, 2 home works	
Language:	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* taking place in the femtosecond and attosecond time scales in *atoms and molecules*. This will include multiple pulse spectroscopy, quantum interferences between indistinguishable pathways, control of atomic and molecular dynamics, interpretation of spectra and of scattering cross sections in terms of time correlation functions and in terms of potential energy surfaces, femtosecond and attosecond physics, and finally strong field non-linear physics.

All phenomena will be introduced and explained from a *time-dependent quantum mechanical perspective*.

Course prerequisites: Quantum Mechanics courses of 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 grades will be based on the two homework assignments (20%), and on a final exam (80%). Collaboration, limited to two students, on each homework assignment is allowed.

SYLLABUS

I – Time-Dependent Quantum Dynamics

Time-dependent Schrödinger equation, wave packets, quantum-classical correspondence, quantum revivals.

II – Phase-space representation of Quantum Mechanics

Wigner representation of wave functions and density operators, decay and dephasing, correlation functions and atomic or molecular spectra, applications in scattering theory, *Feynman* path integration.

III – Approximate solutions of the time-dependent Schrödinger equation

Representations in quantum mechanics, time-dependent perturbation theory, adiabatic dynamics and sudden approximation, *Wentzel-Fermi* golden rule, periodic Hamiltonians and *Floquet* theory, variational principal.

IV – 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 propagation.

V – 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.

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 laser-matter interaction in nowadays explicitly time-dependent experiments: wave packets, correlation functions, semi-classical methods, and numerical methods. The everlasting development of new laser sources renders this knowledge a pre-requisite in today's research in atomic, molecular and optical physics. You will be able to solve relatively simple time-dependent quantum problems analytically and to design numerical approaches for more complex situations.

Course code:	**Optical properties of solids**	Semester 1
Contributes to:	M2 Laser-Optics-Matter	

Course director: Course teachers ;	Isabelle Robert-Philip (LPN) & Jean-Sébastien Lauret (ENS Cachan)	
Volume: Period:	33 hours Weeks 37-48 with written examination week 49.	**3 ects**
Assessment:		
Language of tuition:	French or English	

Course Objectives:

This course deals with the light mater interaction. In particular, it covers the optical properties of solid state materials. The different natures of optical transitions are addressed and related to the nature of the material: molecular crystals, III-V semi-conductors, colour centres etc… The relaxation of optical excitations is also covered during the course. All these features are put into regards with the use of these materials both for modern physics experiments (single photon sources, quantum information, polariton condensates etc…) and for applications in optoelectronic devices (photovoltaics, lasers etc…). The course is composed of lectures, tutorials and 2 illustrative seminars. Classical tutorials as well as tutorials based on the analysis of recent research papers will be given.

Course prerequisites:

- Solid State Physics (M1) or the 3h pre-requesite course of LOM master (see website)
- Quantum physics (M1)
- Electromagnetism (L3)

Syllabus

1) Classical response
  * Lorentz model of light-matter interaction (Dielectric constant, comparison with experiments…)
  * Drude Model (dielectric constant, conductivity, relaxation time, …); limits of the Drude model

2) Quantum response
  * Einstein coefficients (rate equations, links between the different coefficients…)
  * Transition probability and oscillator strength (Fermi Golden rule, light matter hamiltonian…)

3) Absorption, Luminescence and Excitons
  * Interband absorption (Matrix element, Density of states, selection rules…)
  * Excitons (definition, Wannier excitons, Frenkel excitons…)
  * Luminescence (photoluminescence, Cathodoluminescence, Electroluminescence)

4) Phonons, diffusion
  * Harmonic approximation (hypothesis, limits, potential energy…)
  * 1D mono atomic solid model (acoustic mode)
  * 1D mono di-atomic solid model (optical mode)
  * Quantum treatment of phonons
  * Inelastic light diffusion

5) Molecular materials and Colored centers
  * Molecular electronic states
  * Vibronic transitions
  * molecular configuration diagram
  * Franck-Condon Principle

6) Optical properties of metals
  * Plasmons

7) Semiconductor quantum wells and dots
  * Principle of 2D, 1D and 0D quantum confinement
  * Fabrication of semiconductor heterostructures
  * Electronic states (envelop function formalism, density of states, exciton in quantum wells, Fermi Golden rule, etc…)
  * Absorption (interbands, inter subbands) and emission of light
  * Quantum Stark effect

On completion of the course students should be able to:

First, the student will have a broad overview of the basics about optical properties of solids, from semiconductor to molecular materials. Secondly, the student will be enabled to deepen various optical and optoelectronic phenomena used in modern physics experiments and in devices.

Textbooks/bibliography: see for instance

- Ashcroft et Mermin « Solid State Physics » EDP Sciences
- M. Fox « Optical properties of solids », Oxford master series

Course code:	**Interaction between light and atoms**	Semester 1
Contributes to:	M2 Laser – Optics - Matter	

Course director: Course teachers :	David Clément (Institut d'Optique) & Thierry Chanelière (CNRS LAC)	
Volume: Period:	33 hours Weeks 37-48 with written examination week 49.	**3 ects**
Assessment:		
Language of tuition:	English or French	

Course Objectives:

- sujet du cours : interaction d'un champ lumineux avec un ensemble de systèmes quantiques.

- l'accent est mis sur la cohérence atomique, vue comme une mémoire de phase optique portée par les atomes. On passe de l'échelle de l'atome à celle d'un ensemble par le biais de la polarisation macroscopique.

- nous avons recours à 2 approches complémentaires: (i) une approche macroscopique fondée sur la causalité (ii) une approche microscopique à partir de la matrice densité et des équations de Bloch optiques.

- nous insistons sur deux notions fondamentales associées à la matrice densité: (i) l'idée de mélange statistique, (ii) l'apparition de la décoherence quantique via une trace partielle.

- cette description est appliquée aux forces radiatives, à la lumière lente, aux réponses radiatives retardées telles que l'écho de photon

Course prerequisites and corequisites :

- Electromagnétisme classique : équations de Maxwell dans un diélectrique, polarisation macroscopique, susceptibilité électrique, approximation de l'enveloppe lentement variable (Slowly Varying Envelope Approximation)
- Mécanique quantique élémentaire, équation de Schrödinger d'un système à deux niveaux en interaction quasi résonnante avec un champ électromagnétique classique, approximation de l'onde tournante (Rotating Wave Approximation)
- Transformation de Fourier
- Equations différentielles linéaires

Syllabus

Chapitre I Réponse radiative en régime linéaire - Rappels
A. Équation d'onde – diélectrique non-chargé
B. Réponse linéaire, susceptibilité, causalité, relations de dispersion
C. Résolution de l'équation d'onde
D. Coefficient d'absorption et indice de réfraction
E. Propagation sans déformation : enveloppe et onde porteuse, vitesse de phase et vitesse de groupe

Chapitre II Filtrage à travers un profil d'absorption structuré
A. Filtrage par un profil d'absorption étroit : réponse liée au terme d'absorption seul – violation de la causalité ; réponse liée à la dispersion – rétablissement de la causalité ; échantillon optiquement épais – atténuation de l'aire
B. Profil d'absorption sinusoïdal : réponse retardée :; susceptibilité, champ transmis, énergie transmise
C. D'où vient la réponse retardée ?

Chapitre III Modèles microscopiques simples d'interaction Lasers – Atomes
A. Electron élastiquement lié
B. Approche d'Einstein: Rate équations

Chapitre IV L'atome à 2 niveaux dans un champ électromagnétique.
A. Dipôle atomique, Oscillations de Rabi, Franges de Ramsey
B. Nécessité d'introduire la relaxation.

Chapitre V. Matrice densité, incorporation de processus de relaxation.
A. Notion de trace partielle
B. Equations de Bloch Optiques (EBO)

Chapitre VI. Application des EBO à l'atome à 2 niveaux
A. la susceptibilité complexe
B. forces radiatives pour un atome à 2 niveaux

Chapitre VII. EBO pour un atome à 3 niveaux.
A. Transparence électromagnétiquement induite (EIT)
B. Doublet Autler - Townes

Chapitre VIII. Traitement de la dissipation par une énergie complexe: un autre regard sur le EIT

Chapitre IX EBO et excitation impulsionnelle
A. Résolution formelle

B. Perturbations dépendant du temps

Chapitre X EBO et variables macroscopiques : Polarisation et susceptibilité en régime linéaire, rayonnement de précession libre

A. Polarisation en régime linéaire
B. Mémoire de l'excitation
C. Expression atomique de la susceptibilité
D. Réponse percussionnelle à une impulsion courte. Rayonnement de précession libre : réponse linéaire ; résolution de l'équation d'onde dans le domaine temporel

Chapitre XI Echo de photon en régime de champ faible

A. Excitation par une paire d'impulsions séparées dans le temps: rappel sur l'excitation par une impulsion; modification des populations par deux impulsions séparées dans le temps
B. Compensation du déphasage inhomogène, écho de photon : filtrage linéaire à travers le réseau spectro-spatial ; polarisation macroscopique ; solution de l'équation d'onde et condition d'accord de phase ; écho à deux impulsions; spectroscopie d'absorption et transitoires cohérents

Chapitre XII Représentation du vecteur de Bloch, manipulation cohérente

A. Vecteur de Bloch, sphère de Bloch : construction du vecteur de Bloch et précession de Larmor ; quelques propriétés du vecteur de Bloch
B. Echo à deux impulsions : effet d'une impulsion π ; Formation de l'écho à partir d'une première impulsion faible ; Optimisation de l'amplitude du signal d'écho

On completion of the course students should be able to:

- Comprendre un article scientifique qui utilise les équations de Bloch optiques
- maîtriser la réponse non instantanée et le rôle joué par les cohérences atomiques (par opposition aux situations habituelles de l'optique-non linéaire en régime pulsé, ou de la physique des lasers)
- maîtriser les mécanismes d'échange de phase spatiale et spectro-temporelle entre atomes et champ en régime transitoire
- comprendre l'excitation collective d'un ensemble de systèmes quantiques
- étendre les notions acquises à l'excitation par un champ non-classique et aborder la physique quantique macroscopique et l'information quantique, illustrée en particulier par les mémoires quantiques pour la lumière

Textbooks/bibliography:

- G. Grynberg, A. Aspect, C. Fabre, "Introduction aux lasers et à l'Optique Quantique", Ellipses 1997
- L. Loudon, "The quantum theory of light", 3rd Ed. Oxford, 2003
- M. Scully, S. Zubairy, "Quantum Optics", Cambridge, 1997.
- L. Allen, J. Eberly, "Optical Resonance and 2 level atoms", Dover, 1975 (vente en ligne: environ 13€)

Course code:	**Quantum Optics**	Semester 1
Contributes to:	M2 Laser – Optics - Matter	

Course director: Course teachers:	Chris Westbrook (LCF) & Antoine Browaeys (LCF)	
Volume: Period:	30 hours Sept. – Dec.	**3 ects**
Assessment:	A set of homeworks will also contribute to the finale grade (~15-20%)	
Language of tuition:	English	

Course Objectives:

- Give a simple introduction to quantization of the electromagnetic field and its interaction with an atom
- Show how some typical optics problems are treated using quantized fields: the photo-electric effect, light detection, shot noise (the standard quantum limit), coherence, the Hanbury Brown Twiss effect
- Discuss effects that cannot be explained with a classical field: spontaneous emission, behavior of single photon states, anti-bunching, the Hong Ou Mandel effect, measurements below the standard quantum limit

Course prerequisites and corequisites:

1. Classical electrodynamics, especially use of the Coulomb gauge and dipole radiation
2. Elementary quantum mechanics: Dirac notation, the harmonic oscillator, the hydrogen atom, notions of spin and angular momentum, a little perturbation theory

Syllabus

1. Blackbody radiation according to Planck, Einstein and Bose. Quantization of the harmonic oscillator
2. Quantization of the electromagnetic field. Number states, coherent states, thermal states, squeezed states
3. Interaction with atoms: dipole approximation, perturbation solution for both a classical and a quantum field. Einstein's A and B coefficients revisited
4. Spontaneous emission in vacuum and in a cavity, Fermi's 2nd golden rule. Weisskopf Wigner approach.
5. Photo-electric effect for classical and quantum fields. Theory of photon detection. Action of a beam splitter.
6. Theory of photon detection for multiple photons and multiple frequencies, Hong Ou Mandel Effect
7. Quantum coherence, Hanbury Brown Twiss effect.
8. Non-linear quantum optics, single photon sources, squeezing.
9. Interferometry, noise and entanglement
10. Other topics: teleportation, quantum information, the Jaynes-Cummings model, non-destructive photon detection

On completion of the course students should be able to:

- have a strategy to determine whether a light field is non-classical
- understand a paper discussing modification of spontaneous emission rates and Purcell factors
- understand a paper discussing photon bunching or antibunching
- understand a paper about beating the standard quantum limit in a measurement

Textbooks/bibliography:

- C. Gerry, P.L. Knight, "Introductory quantum optics" Cambridge, 2005.
- G. Grynberg, A. Aspect, C. Fabre, "Introduction aux lasers et à l'Optique Quantique", Ellipses 1997.
- L. Loudon, "The quantum theory of light", 3rd Ed. Oxford, 2003.
- M. Scully, S. Zubairy, "Quantum Optics", Cambridge, 1997.

Course code:	**Nanophotonics**	Semester 1
Contributes to:	M2 Laser – Optics - Matter	

Course director: Course teachers:	Philippe Lalanne (LP2N) & Henri Bénisty (LCF) Christophe Sauvan (LCF)	
Volume: Period:	30 hours Sept. – Dec.	**3 ects**
Assessment:	Written Exam	
Language of tuition:	English	

Course Objectives: To introduce
1) Fundamentals of electromagnetism of nanostructures, and
2) applications of artificial optical nanostructures, and eventually
3) Combination of these optical structures with basic structures for electronic confinement (quantum well and quantum dots) for enhanced light matter interaction (Purcell effect, etc.)

Course prerequisites and corequisites:
Basics of waves, diffraction, guiding, semiconductors.

Syllabus

Propagation of waves in periodic media is at the heart of many physical phenomena, to start with the formation of bands for electrons in solids.

This course addresses the same issue in optics.

We start, in particular, with the notion of Bloch modes in optical artificial materials, that is materials structured at sub-wavelength scale. Thanks to the recent progresses in nanofabrication methods, such materials are massively investigated nowadays.

By analogy with electrons, we introduce the forbidden photonic band gap and also the idea of artificial materials. These latter lead in particular to the possibility of artificially synthesizing materials that display properties otherwise not found in nature.

Theoretical notions such as density-of-states (DOS), light-line (aka light cone), slow light, etc. (are systematically illustrated by applications that have arisen from recent nanophotonics literature, notably :
- Photonic crystals (mainly 1D and 2D),
- metamaterial
- and diffractive optics.

The concept of enhanced light-matter interaction in nanoparticles or as a function of confinement in general, is substantiated : Purcell effect, light extraction, strong coupling. This is also an opportunity to describe along their main lines (i) the basic physics of electronic confinement in nanostructures and (ii) their elaboration methods as well.

The course is illustrated by a few training sessions (~3 x 1.5h) aimed at rackling with some more depth fundamental concepts such as
- slow light at photonic band edges or
- the regime of negative refraction, a more recent concept.

On completion of the course students should be able to:
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Textbooks/bibliography:

Lecture notes (Ph Lalanne) , Training session texts (C. Sauvan),

Lecture Slides (H. Benisty), copy of papers(4x APL) used for HB exam.

Lecture notes available at : http://paristech.iota.u-psud.fr/site.php?id=348

[1] H. Benisty, J.-M. Gérard, R. Houdré, J. Rarity, and C. Weisbuch, Eds., Confined Photon Systems : Fundamentals and Applications (Lecture Notes in Physics. Heidelberg: Springer, 1999, (Target some Chapters)

[2] J.-M. Lourtioz, H. Benisty, V. Berger, J. M. Gérard, D. Maystre, and A. Tchelnokov, Photonic Crystals, Towards Nanoscale Photonic Devices. Heidelberg: Springer, 2005.

[3] H. Benisty and C. Weisbuch "Photonic crystals," in Progress in Optics. vol. 49, E. Wolf, Ed., ed Amsterdam: Elsevier, 2006, pp. 177-315.

General books on multilayers, waveguides, distributed feedback, basics of density-of-states, optoelectronics

[4] A. Yariv, Quantum Electronics. New York: Wiley, 1989.

[5] A. Yariv and P. Yeh, Optical waves in crystals. New York: Wiley, 1984.

[6] L. A. Coldren and S. W. Corzine, Diode lasers and photonic integrated circuits. New-York: Wiley, 1995.

[7] E. Rosencher and B. Vinter, Optoélectronique. Paris: Masson, 1997.

[8] C. Weisbuch and B. Vinter, Quantum Semiconductor Structures: Fundamentals and applications. Boston: Academic Press, 1991.

Course code:	**Mécanique quantique approfondie**	Semester 1
Contributes to:	M2 Laser – Optics - Matter	

Course director: Course teachers :	Djamel BENREDJEM & Laurence PRUVOST	
Volume: Period:	27 hours Weeks 37-47 with written examination week 49.	**3 ects**
Assessment:		
Language of tuition:	English or French	

Course Objectives:
Le cours complète le cours de mécanique quantique de type L3 ou M1. Son objectif est d'appréhender des méthodes fondamentales, analytiques ou semi-analytiques, pour traiter des problèmes classiques de mécanique quantique.
- les objectifs du cours (décrit dans cette boîte) : rappels sur la composition des moments cinétiques, les rotations et le théorème de Wigner-Eckart. Seconde quantification. Systèmes de particules identiques.

Course prerequisites and corequisites:
Le niveau requis intègre les enseignements de mécanique quantique de L3 et M1.
Plus particulièrement il est demandé de connaitre
- l'équation de Schrodinger, en particulier à une dimension.
- L'oscillateur harmonique
- L'atome à deux niveaux en interaction avec une onde laser dans l'approximation des grandes longueurs d'ondes. (ce point pourra être vu dans un autre cours proposé au M2).

Syllabus
Cours de D. Benredjem
Rappels : Moments cinétiques et rotations
Moments cinétiques (Opérateurs de rotation, matrices de rotation, invariance par rotation)
Couplage de moments cinétiques (Changement de base, Symboles 3j, Trois moments cinétiques)
Opérateurs tensoriels (tenseurs, opérateurs tensoriels irréductibles, théorème de Wigner-Eckart)
Quantification du champ électromagnétique
Description classique (équations de Maxwell, jauge de Coulomb, champ libre)
Description quantique (quantification oscillateur harmonique, opérateurs de création et d'annihilation)
Quantification du champ électromagnétique (Opérateurs de création/annihilation, états quantiques du champ électromagnétique, hamiltonien du champ électromagnétique, potentiel vecteur, champ électrique, hamiltonien)
Interaction atome-champ électromagnétique
Interaction d'un atome avec un champ électromagnétique (hamiltonien d'un atome, hamiltonien du champ électromagnétique), Hamiltonien d'interaction)
Différents processus (absorption, émission d'un photon, diffusion élastique)
Systèmes de particules identiques
Espace des états
Permutation (opérateur de permutation, transformation des observables, opérateur de transposition)
Kets complètement symétriques/anstisymétriques
Postulat de symétrisation (Généralités, Système de deux particules, Généralisation à N particules)

Cours de L. Pruvost
Cours 1 : Puits carré avec une barrière infinie.
1. Equation de Schrödinger. Exemples physiques décrits pas le puits.
2. Etats liés. Energies, fonctions d'onde, conditions aux limites. Résolution de l'équation de quantification pour un puits profond et pour un puits quelconque.3.
3. Etats du continuum. Etats de grande énergie. Etats quasi-liés.
4. Etats d'énergie nulle. Notion de longueur de diffusion. Applications et exercices.

Cours2 : Méthode d'approximation semi-classique WKB.
1. Equation de Schrödinger et mécanique classique. Point tournant. Région classiquement permise et interdite. 2.
2. Solution WKB.
3. Raccord au point tournant et fonction d'Airy. Fonction d'onde WKB.
4. Quantification de Bohr-Sommerfeld.
5. Applications : puits carré, ou oscillateur harmonique, ou formule de Leroy-Bernstein.

Cours3 : Couplage discret-continuum.
1. Généralités sur les Equations de Schrödinger couplées.
2. Cas de deux niveaux couplés.
3. Couplage d'un niveau discret à un continuum. Règle d'or de Fermi. Modélisation du continuum. Equation aux valeurs propres.

Résolution graphique. Profil de raie lorentzien.
4. Applications : les profils de Fano. Le couplage au bord d'un continuum et la résonance de Feshbach.

Cours 4 : Ensemble de N particules identiques. Théorie du champ moyen. Equation de Gross-Pitaevski.
1. Hamiltonien de N particules et hypothèses.
2. La méthode variationnelle.
3. Champ moyen. Equation de Gross-Pitaevski.
4. Pseudo-potentiel pour décrire l'intéraction de 2 atomes. Lien avec la longueur de diffusion. Application au condensat de Bose-Einstein. Equation de Thomas-Fermi. Exercices.

Cours 5 et 6: Atome en interaction avec un champ quantique. Théorie de l'atome habillé.
1. Rappels sur le champ quantifié et le hamiltonien d'interaction atome-champ.
2. Ensemble atome+champ et sa base. Notion de multiplicité.
3. Résolution dans une multiplicité et hypothèses de travail. Base habillée. Diagramme d'énergie et expression du light-shift.
4. Applications effet Autler-Townes. Le triplet de Mollow et le spectre d'absorption d'un atome soumis à un champ fort. La force dipolaire.

On completion of the course students should be able to:

Cours de LP : On demande que l'étudiant connaisse les solutions des équations différentielles simples (second ordre à coefficients constants, oscillateur harmonique par exemple) le développement de Taylor et les intégrales simples mettant en jeu des fonctions sinusoïdales, et exponentielles.
On demande que l'étudiant connaisse la mécanique du point, soumis à une force dérivant d'un potentiel.

Textbooks/bibliography:

Cours de DB :
- **Mécanique quantique ,** A. Messiah, Dunod, Paris
- **Introduction aux lasers et à l'optique quantique,** G. Grynberg, A. Aspect, C. Fabre, Ellipses, Paris
- **Processus d'interaction entre photons et atomes ,** C. Cohen-Tannoudji, J. Dupont-Roc, G. Grynberg, InterEditions/Editions du CNRS, Paris

Cours de LP :
- Mecanique quantique C Cohen-Tannoudji, B Diu, F Laloe, Hermann.
- Photons et atomes - Introduction à l'électrodynamique quantique , C Cohen-Tannoudji, J. Dupont-Roc, G. Grynberg, InterEditions/Editions du CNRS
- Theoretical atomic physics, H Friedrich, Springer.

Course code:	**Statistical Optics**	Semester 1
Contributes to:	M2 Laser-Optics-Matter	

Course director: Course teachers ;	D. Clément and N. Westbrook	
Volume: Period:	33 hours Weeks 37-49 with written examination week 50.	**3 ects**
Assessment:		
Language of tuition:	English or French	

Course Objectives:
Introduction to statistical tools to treat light disturbances
Definition of temporal and spatial coherence of light sources with a statistical approach
Description of the speckle phenomenon (mainly Fourier speckle) and its manifestations

Course prerequisites:
Fresnel and Fraunhoffer diffraction theory
Application of diffraction theory to simple imaging systems
Fourier filtering
Basic mathematics on random variables

Syllabus
Reminder on coherent and incoherent imaging (impulse response functions, transfer functions) (1 lecture)
Introduction to statistical optics (1 lecture)
Temporal and spatial coherence of optical waves (3 lectures)
Speckle phenomenon and applications through seminars on current research topics (4 lectures)
Photo-detection (1 lecture)

On completion of the course students should be able to:
use statistical tools to accurately describe and understand optics and light sources ; master concepts of second order coherence and their applications to current research and technology; describe and calculate Fourier speckle patterns and understand their implications

Textbooks/bibliography:
Introduction to Fourier optics, Goodman Joseph W. [prerequisites on diffraction and Fourier filtering]
Statistical Optics, Goodman Joseph W. [prerequisites on random variables: Chapter 2]
Fundamentals of photonics, Bahaa E. A. Saleh, Malvin Carl Teich [Chapter 10]
Speckle phenomena in optics, Goodman Joseph W.

Course code:	**Approches statistiques en physique moléculaire**	Semester 1
Contributes to:	M2 Laser-Optics-Matter	

Course director: Course teachers ;	Pascal Parneix Pascal Parneix (ISMO) and Cyril Falvo (ISMO)	
Volume: Period:	24 hours Weeks 36-48 with written examination week 49.	**3 ects**
Assessment:	Written examination and analysis of a scientific paper	
Language of tuition:	French	

Course Objectives:
Understanding the intramolecular dynamics in large excited molecule or cluster
Understanding the effect of vibronic couplings on the intramolecular dynamics
Exploring the different relaxation pathways for a large molecule
Effect of an environment on the molecular optical response

Course prerequisites:
Quantum mechanics :
Mécanique quantique (Tomes I et II), Claude Cohen-Tannoudji, Bernard Diu, Franck Laloë, Editor: Hermann
Molecular physics :
Molecular quantum mechanics, Peter Atkins and Ronald Friedman, Editor: Oxford University Press
Statistical physics :
Elements de physique statistique, Bernard Diu, Danielle Lederer and Bernard Roulet, Editor: Hermann

Syllabus
Chapter 1: Introduction to the intramolecular dynamics
- **Born-Oppenheimer approximation**
- **Quantum yield**
- **Simple model for taking into account non-adiabatic couplings**
- **Time-dependent and time-independent quantum approaches**
- **Statistical limit and irreversibilty**

Chapter 2: Electronic energy relaxation in the statistical limit
- **Internal conversion**
- **Intersystem conversion**

Chapter 3: Vibrational Energy relaxation
- **Intramolecular Vibrational Redistribution**
- **Statistical approaches for fragmentation, Isomerisation and IR radiative relaxation**
  - **Classical and quantum vibrational density of states**
  - **Canonical and microcanonical properties of a large molecular system**
  - **Isomer superposition model for a complex potential energy surface**
  - **Transition State Theory**

Chapter 4: Molecular spectroscopy and linear response theory
- **Optical response and auto-correlation function**
- **Fluctuation-dissipation theorem**
- **Classical approximation**

Chapter 5: Molecules coupled to an environment
- **Bath as stochastic process, Kubo theory**
- **Bath as harmonic oscillators, cummulant Gaussian expansion**

On completion of the course students should be able to:
The students should be able to identify the coupling operators and the molecular parameters which influence the intramolecular dynamics. They should be able to identify the effect of the intramolecular dynamics on the spectral features. They should be able to use some simple or more refined models for theoretically describing the intramolecular dynamics. From the illustration of experiments proposed in the course, they should be able to identify some typical experimental set-up for studying complex intramolecular dynamics.

Textbooks/bibliography:
Radiationless transitions in polyatomic molecules, Emile S. Medvedev, Vladimir I. Osherov, Editor: Springer-Verlag
Energy landscapes: Applications to clusters, biomolecules and glasses, David Wales, Editor: Cambridge university press
Statistical physics of nanoparticles in the gas phase, Klauss Hansen, Editor: Springer
Principles of nonlinear optical spectroscopy, Shaul Mukamel, Editor: Oxford university press
Statistical Physics II, R. Kubo, M. Toda and N. Hashitsume, Editor: Springer-Verlag
Statistical Mechanics, D. A. McQuarrie, Editor: Harper&Row

Course code:	**Structure moléculaire et transitions optiques**	Semester 1
Contributes to:	M2 Laser-Optics-Matter	

Course director: Course teachers ;	Niloufar Shafizadeh(CR-CNRS_ISMO) Jean-Hugues Fillion (Professeur UPMC-LERMA) –Séverine Boyé-péronne (MCF UPS-ISMO)	
Volume: Period:	24 hours Weeks 36-49 with written examination week 50.	**3 ects**
Assessment:	Written examination	
Language of tuition:	French	

Course Objectives: Is to describe the interaction between **an isolated molecule and an electromagnetic radiation, i.e, an introduction to the molecular spectroscopy.**
We will present
*The models which describe the molecular electronic, vibrationnal and rotationnal wave function and their symmetries .
*The approximations which allow to describe the nuclear motion in molecules (vibration and rotation).
*The coupling between the orbital angular momentum and the rotational angular momentum
*The selection rules which allow the interaction between the radiation and the molecules
This option is an direct approach for describing the electronic structure of isolated molecules
T

Course prerequisites:
.Bibliographie : Mécanique Quantique C.Cohen Tannoudji, B. Diu et F. Laloë
or
.Physique Atomique et Moléculaire (M1 Physique fondamentales Université Paris-Sud)
or
.Atomic and molecular physics (M1 Physics for Optics and Nanosciences)
Course Corequisites :Structure et dynamique électronique

Syllabus
Chapitre I- Les bases pour comprendre la structure moléculaire
Chapitre II- Structure électronique d'une molécule diatomique
Chapitre III- La molécule avec spin électronique -Interaction spin-orbite
Chapitre IV- Structure vibrationnelle et rotationnelle d'une molécule diatomique
Chapitre V- Interaction molécule- rayonnement
Chapitre VI- Moment de transition pour une transition dipolaire électrique
Chapiptre VII- Molécules Polyatomiques
Chapiptre VIII-Méthodes actuelles de la spectroscopie :Transition multiphotonique et Spectroscopie d'absorption intra cavité

On completion of the course students should be able to:
The students will be able to analyse a molecular spectrum and extract from it informations on the molecular structure , geometry and the energy levels of the system.

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*
A ***Jeffrey Steinfeld** *Molecules And Radiation: An Introduction To Modern Molecular Spectroscopy*

Course code:	**Plasma Physics**	Semester 1
Contributes to:	M2 Laser-Optics-Matter	

Course director: Course teacher :	Patrick Mora Patrick Mora (Ecole polytechnique)	
Volume: Period:	27 hours Weeks 36-41 with written examination week 42	**3 ects**
Assessment:	written examination	
Language of tuition:	English or French	

Course Objectives:
To give an introduction to plasma physics

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.
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:
distinguish the main waves propagating in an unmagnetized plasma, and caculate their dispersion relation and their phase velocity

Textbooks/bibliography:
J.-M. Rax, Physique des plasmas, Dunod 2005 (in french)

Course code:	**Non-Equilibrium Statistical Physics**	Semester 1
Contributes to:	M2 Laser-Optics-Matter	

Course director: Course teachers ;	Denis Grebenkov	
Volume: Period:	27 hours Weeks 44-50 with written examination week 50.	**3 ects**
Assessment:	Written examination	
Language of tuition:	English or French	

Course Objectives:
Introduction to non-equilibrium statistical physics; presentation of modern problems, physical principles and mathematical methods for analysis of various diffusive processes; illustration of these concepts for several biophysical applications.

Course prerequisites:
Basic statistical physics, basic mathematical physics, basic probability course

Syllabus
Lecture 1: Brown's experiment; probability as lack of information about the detailed classical dynamics; central limit theorem, Gaussian propagator and its properties; diffusion equation; passage from micro- to macro-dynamics
Lecture 2: Langevin equation as a microscopic description; Fourier/Laplace transform as methods of solution; standard examples for overdamped limit (Brownian motion and Ornstein-Uhlenbeck processes); naive derivation of the Fokker-Planck equation; Ito's formula; forward and backward equations
Lecture 3: Generalized Langevin equation; friction memory kernels; anomalous behavior; hydrodynamic effects;
Lecture 4: Fluctuation-dissipation theorem; ergodicity
Lecture 5: Continuous Time Random Walks as an alternative model for anomalous diffusion; fractional diffusion equation; weak ergodicity breaking
Lecture 6: Application to biophysics: optical trapping, FRAP (fluorescence recovery after photobleaching), FCS (fluorescence correlation spectroscopy)
The lectures will be complemented by practical works

On completion of the course students should be able to:
Describe and analyze various natural phenomena governed by non-equilibrium statistical physics

Textbooks/bibliography:
P. L. Krapivsky, S. Redner, E. Ben-Naim, A Kinetic View of Statistical Physics (Cambridge University Press, 2010)

Course code:	**Optics Labworks**	Semester 1
Contributes to:	M2 Laser-Optics-Matter	

Course director: Course teachers ;	Fabienne Bernard (IOGS)	
Volume: Period:	27 hours Weeks 37-42	**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