Physics, Photonics, Nanotechnology (PPN) Master

- ## First year (M1) programme

Solid-state physics and soft matter (Alain Dereux / Patrick Senet / Adrien Nicolaï)

Quantum physics – Quantum optics – Atomic & molecular physics (Stéphane Guérin / Hans Rudolf Jauslin / Vincent Boudon / Dominique Sugny)

Signal Processing: Signal analysis, data analysis, data acquisition **(Aurélien Coillet, Bernard Sinardet)**

Numerical methods for physics (Frédéric Holweck / Matthieu Sala / Jonas Lampart)

Guided optics and opto-electronics (Patrice Tchofo-Dinda)

Laser Technologies (Olivier Musset)

Nonlinear optics: Fundamentals of nonlinear optics, materials for nonlinear optics **(Frédéric Chaussard / Frédéric Smektala / Pierre Mathey)**

Fiber and optical communications (Philippe Grelu / Patrice Tchofo-Dinda)
Microscopies: Scanning probes (AFM, SNOM), Electron microscopies (TEM, MEB) **(Eric Lesniewska / Benoit Cluzel)**

Micro-nano fabrication & clean room (Franck Chollet / Laurent Markey)

Lasers : Fundamentals of laser, Gaussian optics **(Olivier Faucher, Edouard hertz, Frédéric Chaussard)**

Lab project (supervised by one of the teacher / researcher of the ICB Lab)

French language & culture (Nathalie Porebinski / Cyril Paugam)
Soft skills (Rebecca Chamberlain)
Industry seminar (Jean-Renaud Dumas)

- ## Second year (M2) programme

Femtosecond science: from concepts to applications (Olivier Faucher)

The course is related to the fundamental concepts and applications of ultra-short (femtosecond) lasers. In the first part, the linear and nonlinear optical phenomena encountered in the propagation of an intense and ultra-short laser pulse are described. We derive simple formulas for evaluating spatial and temporal pulse distortions depending on the input energy of the laser and the material media. The second part is devoted to simple analytical models developed within the framework of perturbation theory. They provide useful tools for the description of femtosecond processes like, for instance, wave packet analysis measured though pump-probe techniques, production of terahertz radiations, photon echoes, parametric generation of the new wavelengths, and CARS spectroscopy.

Femtosecond laser pulses: properties, characterization and manipulation (Edouard Hertz)

The lecture deals with the characterization and manipulation of ultrashort laser pulses. The first part will be dedicated to the characterization of femtosecond pulses and how to extract some specific and important parameters: energy, spectrum, temporal shape, and wavefront. Second part will focus on the shaping of laser pulses in spatial and time domain. Applications and possibilities opened in the context of coherent control will be then discussed.

Nonlinear Fiber Optics (Philippe Grelu / Guy Millot)

This course introduces the fundamental physical effects and concepts that underlie the propagation of short and ultrashort optical pulses in dielectric waveguides. It elaborates on the major dispersive effects that generally dominate the first stages of propagation of short pulses within passive optical fibers: chromatic dispersion and Kerr nonlinearity. This allows to define several propagation regimes, with an emphasis on optical soliton propagation, along with a variety of fascinating nonlinear phenomena, such as self-phase modulation, four-wave mixing, modulation instability, optical rogue waves and supercontinuum generation. The contributions of Raman and Brillouin scattering in optical fibers are also discussed, and the notions of the course are illustrated in the context of optical communications.
Contents:

- Introduction: from nonlinear optics to nonlinear fiber optics.
- Dispersive effects on short pulses. Propagation equation for the pulse envelope.
- Dispersion-induced broadening of Gaussian pulses.
- Nonlinear optics in dielectric fibers. Third-order nonlinear effects.
- The nonlinear Schrödinger equation. Propagation regimes.
- The optical soliton. Bright solitons, high-order solitons, dark solitons.
- Modulation instability.
- Raman and Brillouin scattering in optical fibers.
- Implications for optical communications.
- Supercontinuum generation and optical rogue waves.

Nonlinear optical dynamics & fiber lasers (Philippe Grelu)

We consider in this course the fiber laser cavity as a complex system where pulse propagation is augmented with gain, loss, and a feedback loop effect from the laser cavity. This system allows us to illustrate a recent concept of soliton: the dissipative soliton, and to present the background of nonlinear dynamics, with the concepts of dynamical attractors and bifurcations. Dissipative solitons are localized formations of an electromagnetic field that are balanced through an energy exchange with the environment in presence of nonlinearity, dispersion and/or diffraction. The concept of a

dissipative soliton provides an excellent framework for understanding complex pulse dynamics and stimulates innovative cavity designs. Reciprocally, the field of mode-locked fiber lasers serves as an ideal playground for testing the concept of dissipative solitons and revealing their unusual dynamics. This course highlights striking self-organized pulse patterns such as optical soliton molecules and explains the implications for the design of high-energy mode-locked fiber laser cavities.
Contents:

- Ultrafast fiber lasers and applications.
- From solitons to dissipative solitons.
- Mode-locked fiber laser technology.
- Complex ultrafast cavity dynamics.
- Advanced optical characterization (dispersive time-stretch method).
- High-energy fiber laser architectures.

Advanced topics in nonlinear and ultrafast fiber optics (John Dudley)

We discuss advanced topics relevant to the physics and applications of nonlinear ultrafast optics. Subjects covered include: Ultrashort pulses - description and techniques for characterisation, particularly frequency resolved optical gating; fibre frequency conversion processes including supercontinuum generation and applications; nonlinear localisation effects and optical rogue waves; state-of-the-art topics from the current research literature are also discussed as part of this class.

Quantum engineering and information (Stephane Guerin / Hans-Rudolf Jauslin / Christophe Couteau)

This course proposes an introduction to the basic concepts and techniques of quantum information, quantum computation and, more generally, of quantum technologies.
The concept of quantum technologies encompasses a family of processes that use quantum effects to produce results that are not possible or more difficult with classical physics. In quantum computation quantum mechanics is used to design algorithms that achieve certain results much faster than classical algorithms.
Contents:

- The principles of Quantum Mechanics and applications to Quantum Optics
- Classical and quantum information, bits and qubits, entangled states
- Quantum information: principles and applications - quantum cryptography, quantum teleportation, quantum information by single photons, quantum no-cloning theorem, Bell inequalities
- Quantum computation: quantum gates, quantum algorithms, principles of the state-of-the-art platforms, quantum supremacy

<u>Practical works:</u>
Principle and measurement of a lifetime/radiation decay of an emitter
Non-linear optics: second-harmonic generation (SHG)
Concept and experimental principle of a quantum cryptography protocol
Measurement of the quantum efficiency of an emitting molecule
Single-photon generation and detection

Quantum control and optimal control of quantum systems (Dominique Sugny)

We present in this course the state-of-the-art techniques of optimal control used in quantum dynamics and apply them in different examples coming from Nuclear Magnetic Resonance, Molecular dynamics and Quantum information science. This course covers all the current topics of optimal control theory such as geometric methods and numerical algorithms.

Molecular quantum dynamics (Fabien Gatti, University Paris-Saclay)

This lecture focuses on the usage and current applications of Molecular Quantum Dynamics, the methodology in theoretical chemistry where both the electrons and the nuclei in a molecule are treated with quantum mechanical calculations. Recent success in helping to understand experimental observations in fields like photochemistry, reactive scattering, or femto- and attosecond chemistry and spectroscopy underline that *nuclear quantum mechanical effects* affect many areas of chemical and physical research. Being important to correctly understand many observations in chemical, organic and biological systems, or for the understanding of molecular spectroscopy, the range of applications covered by molecular quantum dynamics comprises broad areas of science: from astrophysics and the physics and chemistry of the atmosphere, over elementary processes in chemistry, to biological processes (such as the first steps of photosynthesis or vision). Strong emphasis is put on an educational presentation of the fundamental concepts, so that the student can inform himself about the most important concepts, like eigenstates, wave packets, quantum mechanical resonances, potnetial energy surface, Born-Oppenheimer approximation, etc. We present illustrative examples of time-dependent quantum mechanics as animations of realistic wave packets with the MCTDH program package (Multi Configuration Time Dependent Hartree calculations) to assist in visualization.

Bose Einstein condensates (Claude Leroy)

After a brief reminder of basic mathematical tools (Lagrangian, impulse, Hamiltonian, Euler-Lagrange equations), the Gross-Pitaevskii equation, which governs the formation of an atomic Bose-Einstein condensate, is proved and all the physical parameters involved are analyzed.
The second part of the lecture demonstrates that the Gross-Pitaevskii equations can be reduced to a non-linear two-level system describing a bath of atomic and molecular Bose-Einstein condensates. It can be derived from the concept of 2:1 Fermi resonance usually introduced in molecular spectroscopy.
State-of-the-art experimental processes allowing the production of atomic Bose-Einstein condensate are detailed and explained.

Open quantum system (Bruno Bellomo)

This lecture covers the following topics:

- Closed and open quantum systems

- The microscopic derivation of master equations
- Application: quantum optical master equation for a two-level atom
- Markovian vs non-Markovian dynamics
- Decoherence and relaxation processes

Atomic and Molecular Spectroscopy (Vincent Boudon / Frederic Chaussard)

After a review of basics of atomics & molecular spectroscopy, this lecture describes the basics of absorption (microwave and infrared) and Raman scattering high-resolution spectroscopy of small polyatomic molecules. We review the difference molecular movements and their interaction with light.
Contents:

- Born and Oppenheimer hypothesis.
- Molecular rotation and vibrations.
- Vibration coordinates.
- Vibration-rotation Hamiltonian in classical mechanics.
- Vibration-rotation Hamiltonian in quantum mechanics.
- Vibration-rotation energy at order 0.
- Generalities on transitions.
- Vibration-rotation energy at order n.

The lecture is completed by exercises to learn how to analyze simple spectra.

Practical works: Diode laser absorption spectroscopy

Nano-optics, Nano-physics and Plasmonics (Gerard Colas des Francs / Alexandre Bouhelier / Benoit Cluzel)

1. Nano-optics
Nano-optics is the study of optical phenomena near or beyond the diffraction limit. The objective of this course is to present principles and applications of nano-optics. We will first discuss light propagation in micronic and submicronic optical waveguides and give a short overview of integrated photonic devices. Next, we will consider micro-optical cavities as a key concept for efficient light-matter interaction with applications such as controlled spontaneous emission, low threshold laser or sensitive biosensors.
A second part will be devoted to optical nanosources. We will briefly present single molecule spectroscopies methods with particular attention devoted to single photon source behavior.
We will give some simple but key concepts for modelling nano-optical systems.

2. Nanophysics and plasmonics
The objective of this course is to present electron confinements effects on the optical properties of matter, mainly semi-conductor and metal materials. After a short review of the optical properties of bulk materials, we will describe optical properties of their nanostructured counterparts.
In a first part, we will consider semi-conductor nanocrystal (quantum dots) for which electron confinement below its mean free path (~10 nm) leads to quantum confinement effects at the origine of size-dependent optical spectra. Full engineering of quantum dots

is therefore possible to achieve bright nanosources at any wavelength for various applications (biolabelling, quantum cryptography, ...)
The second part of this course will concern plasmonics, or so-called optics of metal. It relies on the specific modes (surface plasmon polaritons) sustained by metallic nanoparticles (~dozens of nm) to control the light at a strongly subwavelength scale. Surface plasmon polaritons results from the coupling of a collective oscillation of the free electrons at the metal surface with an electromagnetic wave. An important particularity of these modes is that their confinement can be down to the nanoscale (that is deeply sub wavelength) although at the price of losses. In this part, we will introduce the concept of delocalized and localized plasmons as well as current (surface enhanced spectroscopies, biosensing) or expected (integrated photonics devices, optical nanoantennas,...) applications.

Practical works:
Surface plasmon waves
Optical tweezers
Whispering gallery mode resonators

Nanobiomodelling: Physics for proteins and molecular modelisation (Patrick Senet / Adrien Nicolai)
The course is an introduction to the methods used to simulate proteins and other biological molecules using physics-based models. The basics of ab initio calculations (DFT, Hartree-Fock), semi-empirical approaches (tight binding), classical molecular dynamics, and Monte Carlo methods are reviewed with applications to biosystems in mind. Coarse-grained methods and simplified models of biopolymers are briefly introduced. The simulation methods are presented and discussed in relation to current experimental techniques to probe the dynamics and folding of proteins (FRET, single molecule spectroscopies, SAXS...). The students will apply the methods to solve simple problems (calculation of electronic properties of small molecules, conformations and IR spectra of peptides, normal modes of large proteins...) using resources of the computer center of the University.

Nano-fabrication (Eric Bourillot / Eric Lesniewska / Laurent Markey)

Nanofabrication essentially uses two ways to manufacture nano-objects: the bottom-up approach and the top-down approach. We propose to familiarize students with the top-down technique, called lithography, and used in the laboratory. This conventional manufacturing technique uses the interaction of an incident beam (e-beam or UV) with the material. The techniques of UV lithography and e-beam lithography will be presented as well as techniques of scanning electron microscopy (SEM), thin film deposition (PVD) and reactive ion etching (RIE).

Practical works: PVD + SEM, e-beam lithography, UV lithography, RIE

Vitreous Materials and their Optical Properties (Frederic Smektala)

This course adresses vitreous materials and their optical properties. The lessons are organized in two parts. In the first one, the different techniques of non crystalline solids elaboration are described, the glass transition phenomenon is explained, as well as glasses structure, conditions of glass formation and cristallisation of glasses. The viscosity of glasses is discussed and the different glasses families are presented. In the second part, the optical properties of glasses are treated: transmission, band gap and multiphonon edges, absorption, diffusion, reflexion, dispersion, linear refractive index. The optical properties of the different glasses families are discussed, as well as coloured glasses, luminescent and lasers glasses, glasses for high energy lasers, and nonlinear optical glasses. Finally, optical fibres are presented: fabrication, propagation, transmission, doped fibres for amplification and lasers, photonic crystal fibres and microstructured fibres.

French language & culture (Nathalie Porebinski / Cyril Paugam)

Master thesis / internship in laboratory (academic or private institution) at ICB or anywhere in the world after validation by the pedagogical committee