Europhotonics-POESII Master - MARSEILLE PROGRAM

Version of September, 2016

In blue: option to choose

- S1-UE1 (80h): **Fundamentals in optics & Tutorials** F. Zolla/A. Nicolet/P. Ferrand **(6ects)**
- S1-UE2 (40h): **Light emission (10h)+ Lasers sources (30h)** N. Sanner/K. Belkebir **(3ects)**
- S1-UE3 (30h): **Imaging and systems in optics** H. Giovannini **(3ects)**
- S1-UE4 (50h): **Laboratory practice** F. Wagner **(3ects)**
- S1-UE5 (60h): **Personal Projects** J.-Y. Natoli/H. Giovannini **(6ects)**
- S1-UE6 (60h): **Physics for photonics part I** M. Knoop/M. Kuzmin **(6ects)**
- S1-UE7 (24h): **Language** P. Fournier **(3ects)**

- S2- UE1 (30h): **Signal and images analysis** J.-M. Themlin **(3ects)**
- S2- UE2 (30h): **Guided Optics/Applications of optoelectronic components** G. Renversez **(3ects)**
- S2- UE3 (20h): **Physics for photonics part II** M. Knoop **(2ects)**
- S2- UE4 (30h): **Properties, fabrication and characterization of optoelectronic devices** J.-Y. Natoli **(3ects)**
- S2- UE5 (30h)**: Electron Spectroscopy** T. Angot **(4ects)**
- S2- UE6 (15h)**: Photon Spectroscopy** J. Duboisset **(2ects)** Compulsory for the equivalence of the 2nd semester of KIT
- S2- UE7 (15h): **Introduction to molecular cell biology** M. Mavrakis/L. Le Goff **(2ects)** Compulsory for the equivalence of the 2nd semester of KIT
- S2- UE8 (30h): **Advanced Electromagnetics 1 – Numerical approach** G. Tayeb **(3ects)**
- S2- UE9 (30h): **Laboratory project and practice work** F. Wagner **(3ects)**
- S2-UE10 (20h): **Non linear optics** H. Akhouayri **(2 ects)**
- S2- UE11 (24h): **Language/Culture** P. Fournier **(2ects)**
- S2- Internship: 2 months **(5ects)**

- S3- UE0 (20h): **Tutorials** G. Tayeb **(2ects)**
- S3-UE1 (22h): **Quantum optics** T. Durt **(2ects)**
- S3-UE2 (24h): **Advanced electromagnetics 2** F. Zolla/G. Tayeb **(3ects)**
- S3-UE3 (34h): **Laser sources&applications/matter interaction** N. Sanner/J.-Y. Natoli **(3ects)**
- S3-UE4 (34h): **Optical components and optoelectronics** J. Lumeau **(3ects)**
- S3-UE5 (24h): **Photonics for biomedical applications** S. Brasselet/A. Dasilva **(3ects)**
- S3-UE6 (24h): **Advanced methods for optical instrumentation** B. Epinat **(3ects)**
- S3-UE7 (28h): **Nanophotonics** : S. Enoch/N. Bonod **(3ects)**
- S3-UE8 (32h): **Numerical methods for Electromagnetics** G. Renversez/K. Belkebir **(3ects)**
- S3-UE9 (34h): **Instrumentation for astronomy from ground to space** P. Amram **(3ects)**
- S3-UE10 (30h): **Experimental projects A (3ects)**
- S3-UE11 (30h): **Experimental projects B (3ects)**
- S3-UE12 (24h): **Language** P. Fournier **(2ects)**
- S3-UE13 (20h): **Analysis on Research Topic or Technological Intelligence (3ects)**

S4- **Thesis (30ects)**
Training in a laboratory or in a company (6 months)

M1 Master (1^{st} year) – Detailed content

S1-UE1: **Fundamentals in optics** Frédéric Zolla/André Nicolet/Patrick Ferrand

TUTORIALS
Content adapted to the background of the students evaluated on the basis of a test done at the beginning of the 1st semester.
Objective: The purpose of this series of tutorials is to remind the common background knowledge that is required in all the lectures of the Master.
Program:
Basic mathematical tools (complex number, derivatives, integrals, vector algebra, Fourier transforms), geometrical and physical optics

At the end of this tutoring series, the students must be able
- to perform basic and advanced mathematical derivations,
- to understand the purpose of Fourier analysis, i.e. the effect of some transformation in one domain (shift, derivative, etc.) to the reciprocal domain
- to draw optical rays for an optical system, and to identify conjugated planes,
- to know how to analyze a state of polarization, and how to modify it,
- to write formally conditions of interferences.

ELECTRODYNAMICS
PART ONE - THE A, B, C, D OF ELECTRODYNAMICS
1 Introduction to electrodynamics
    1.1 General introduction and preliminary remarks
    1.2 Fields and potentials
        1.2.1 Fields derived from potentials
        1.2.2 Non uniqueness of allowed potentials
        1.2.3 Lorenz gauge
        1.2.4 Electromagnetic field in Lorenz Gauge
        1.2.5 Coulomb gauge
        1.2.6 Green function-Retarded potentials
2 Electromagnetic Field generated by an arbitrary sources distribution
    2.1 Harmonic Maxwell equations
    2.2 Potentials in harmonic regime
    2.3 Electromagnetic field in harmonic regime
        2.3.1 The magnetic field
        2.3.2 The electric field
    2.4 Radiated fields
    2.5 Radiated energy-Radiated power
        2.5.1 Harmonic regime
        2.5.2 Finite bandwidth signals
3 Multipole Expansion in ω space
    3.1 Preamble
    3.2 Multipole expansion
Set up of the problem
        3.2.1 Multipole expansion of I

6. Determinant
B) GEOMETRY: ALGEBRAIC ASPECTS
7. Geometry and antisymmetry
8. Tensor product, exterior product
9. Determinant, volume measure
10. Scalar product and orthogonality
C) DIFFERENTIAL GEOMETRY
11. Coordinates and geometry
12. Derivation
13. Coordinate basis in geometric spaces
14. d
15. Vector analysis
16. Maxwell equations
D) INTEGRAL CALCULUS
17. Integration
18. Change of variables in integrals
19. Geometric integration of differential forms
20. Stokes theorem
21. Surfaces in R3
E) DISTRIBUTION AND FOURIER TRANSFORM
22. Distribution
23. Fourier Transform
24. Convolution
25. Distributions and geometry
26. Distributions in electromagnetism
F) COMPLEX ANALYSIS
27. Complex functions
28. Complex functions geometry
29. Residue
30. Residue: practical use
G) LAPLACE AND WAVE OPERATORS, GREEN FUNCTIONS
31. Laplace operator
32. Wave equation
33. Green function
34. Green function for the wave equation
35. Dirac distribution and change of variables

S1-UE2: **Light emission, Lasers sources** Nicolas Sanner/Kamal Belkebir

Objectives: This course is an introductory lecture concerning lasers, providing comprehensive description of the physics underlying the operation of lasers. The first part, “Light emission” (10h), introduces the three main processes responsible for light emission (thermal, spontaneous, stimulated). In the second part, “Laser sources” (30h), a comprehensive treatment is provided for the fundamental concepts of lasers physics and the basic operation principles, including light amplification, laser oscillator, laser cavities and laser beams, and a brief introduction to pulsed regimes. Detailed example and tutorials are included. At the end of this module, the student will possess knowledge on principles and operation of laser sources as well as resulting characteristics of laser light.

Prerequisites/Background: Basic knowledge of 3rd year of Physics degree is sufficient prerequisite to allow students to follow this course: wave optics, electromagnetism and basic quantum physics, as treated for example in "Physics" from Serway and Jewett.

Detailed program

Part 1 – Light emission (10h), K. Belkebir

In this part, we focus on several processes responsible for light emission with some practical examples. These processes can be gathered in three groups concerning:

1. *Thermal emission*

This part presents the thermal radiation and its main characteristics as well as recent progress made in the comprehension of such a radiation. We first introduce the thermal radiation in a classical way using the concepts of specific intensity, the Planck function and the Kirchhoff laws. Then, we use the stochastic electrodynamic frameworks to describe more in details the microscopic behaviour of the thermal electromagnetic field.

2. *Luminescence and spontaneous emission*

The microscopic processes of production of light by individual emitters (atoms and molecules) or semi-conductors (LED) are described. The dynamics and time fluctuations of the emitted light are related to these microscopic processes. It gives the opportunity to introduce the concept of non-classical light by studying emission by single emitters like single atoms or molecules.

3. *Stimulated emission*

This part presents the Einstein theory for matter-light interaction and introduces the fundamental concepts at the origin of light amplification and laser sources.

Part 2 – Laser sources (30h), N. Sanner

1. *Introduction*
   - 1.1 Brief historical context… and concepts: blackbody emission, Planck's law, Einstein and the "photon"
   - 1.2 First lasers (gas, crystals)
2. *Photon-atom interaction : basic mechanisms*
   - 2.1 Radiative and non-radiative transitions
   - 2.2 The 3 mechanisms of photon-atom interaction: spontaneous emission, absorption and stimulated emission, and competition between them
   - 2.3 Populations of atomic levels: role of thermodynamics (Boltzmann law), relation between Einstein coefficeints, competition between mechanisms, rate equations
3. *Light amplification*
   - 3.1 Conditions for light amplification: population inversion
   - 3.2 Pumping and population inversion for various atomic systems (2-level, 3-level, 4-level)
   - 3.3 Gain and saturation: saturation of population inversion, saturation of effective gain
4. *The laser oscillator*
   - 4.1 Principle and phenomenological description
   - 4.2 Laser oscillation: Condition on the gain for laser oscillation, laser starting, oscillation in stationnary regime, output laser intensity, efficiency
5. *Laser cavities and laser beams*

5.1 Longitudinal modes of a cavity: FabryèPerot cavity, spectral properties
5.2 Cavity stability: How to make stable cavities (length, mirrors' curvature)?
5.3 Transverse modes of a resonator: Why are laser beams Gaussian? What are their propagation properties?

6. *Pulsed regimes*
   6.1 Q-Switch
   6.2 Modelocking

S1-UE3: **Imaging and systems in optics** Hugues Giovannini/Guillaume Maire

1. Diffraction, scattering, link with the definition of an image.
2. Diffraction in electromagnetics. Treatment with a volume integral approach. Link with Huygens-Fresnel principle. Reminder Fresnel, Fraunhofer diffraction.
3. Link between the diffracted field and the permittivity profile (shape, refractive index) of an object.
4. Near-field, far-field.
5. Consequence of the spatial filtering on the resolution. Optical transfer function, point spread function.
6. Simple case of the Born approximation. Correspondence between the directions of illumination/collection and the accessible information. Diffraction limit.
7. Case of the tomographic diffraction (holographic) imaging.
8. The lens, the mirror. Magnification. Defects. Comments on Fourier optics.
9. Coherent vs incoherent imaging.
10. Field of view.
11. Different practical cases: microscope (air, immersion, fluorescence, confocal), telescope, human eye, binoculars…
12. Comments on the consequences of noise. Comments on the resolution of inverse problems.

S1-UE4: **Laboratory practice** Frank Wagner

- Geometrical optics
- Ray-tracing with Oslo (illustration of the abberations)
- Fourier optics
- Polarization
- Monochromator
- Michelson interferometer
- Spectroscopy
- Photodetectors
- Energy bands
- Holography

S1-UE5: **Personal Projects** Jean-Yves Natoli/Hugues Giovannini

Example of projects chosen in 2014-2015

Numerical Study of laser damage in a nonlinear crystal
Observing the Universe from Space and from the Ground
Raman Spectroscopy of Diamond nanoCrystals
Controlling emission with Metamaterials
How to measure an optical frequency with the best precision?
Development of a pyramid wavefront sensor (PWFS)
Study of stress induced deformation in optical coatings deposited by rf-magnetron sputtering
Plasmonic eigenmodes in graphene nanotriangles
Light propagation and imaging in diffusive media
High dynamic imaging for exoplanet characterisation: study of instrumental vibration in a segmented telescope
Development of an automatic tracking system for dry mass follow-up of live cells

S1-UE6: **Physics for photonics part I** Martina Knoop/Michael Kuzmin

Atomic Physics

1. Mass, size and charge of the atom and the electron
2. Basics of quantum mechanics. Light quanta. Emission and Absorption. Duality wave-particle. Uncertainty relation.
3. The atom picture of Bohr, Rutherford and Sommerfeld (and its limits).
4. The hydrogen atom. Central-field approximation. Spin-orbit coupling.
5. Line broadening and Atoms in external fields.
6. Interactions of atoms with light. Spectroscopy and High-resolution spectroscopy
7. Laser cooling. Traps. Atomic clocks.

Statistical physics

1. Quantum states. Fundamental assumption. Closed system. Equal probabilities. Microcanonical ensemble.
2. Systems in thermal contact. Temperature and entropy. Canonical ensemble.
3. Systems in diffusion contact. Chemical potential. Grand canonical ensemble.
4. Fermi-Dirac's distribution. Fermions. Metals.
5. Bose-Einstein's distribution. Bosons. Bose-condensation. Photons, Planck's distribution.
6. Boltzmann's distribution. Ideal classical gas.

S2-UE1: **Signal and images analysis** Jean-Marc Themlin/Stéphane Grimaldi/Laurent Nony

This lecture will briefly develop the essential tools commonly used to describe continuous-time (analog) and discrete-time signals, images and noise, mostly from a deterministic waveform point of view. Continuous-time waveforms will be represented by direct mathematical expressions or by the use of orthogonal series representations such as the Fourier series. Properties of these waveforms, such as their DC value, root-mean-square (RMS) value, energy and power, magnitude and phase spectrum

(through the Fourier transform), power spectral density, and bandwidth, will be briefly recalled or established. Systems are used to manipulate these waveforms, using various operations like the scalar product, convolution and correlation. In addition, effects of linear filtering will be briefly studied.
Most of these tools can be extended to images, considered as 2D signals depending on two space coordinates (x,y), which can also be described in the frequency domain by a spectrum depending on a spatial frequency. The sampling theorem viewed as a special orthogonal series expansion allows representing an analog signal by a limited number of samples acquired above the Nyquist frequency. The spectrum of a given waveform (discrete-time or analog) can be conveniently calculated using the discrete Fourier transform (DFT), one of the main tools of the so-called "digital signal processing" domain (DSP). Across the lecture, actual systems used in signal storage, transmission and modulation, multiplexing, video signal coding, lossy signal compression (principle of JPEG standard) will be explained.
We want to actively engage the student as early as possible in the actual design of practical signals and systems. Through several hands on laboratories based on MatLab (or its open source equivalent FreeMat), the students will develop useful and realistic "expert systems" and implement their own solutions, e.g. in signal estimation and identification.
At the end of this lecture, the students should have learned a significant amount of signals and systems concepts, tools and theory, have developed an awareness of a number of problems/tasks that signals and systems engineering addresses, and be capable of resolving some signals and systems problems using MatLab, a widespread tool used in R&D worldwide.

S2-UE2: **Guided Optics / optics in Telecommunications** Gilles Renversez

Pre-requisites

Maxwell's Equations and constitutive relations
Plane waves
Basics of second order linear differential equations
Basic linear algebra including eigenvalue problems
Basics of linear operator formalism
Fourier transform

1. General introduction

2. Slab waveguide

-Introduction
-Maxwell equations and other needed equations
-TE/TM splitting
-Propagation equations
-Dispersion equation for the TE case
-General properties of modes
-Symmetric slab case
-Some technological issues

3. Signal propagation in a waveguide

-Extent of a signal
-Evolution of a signal during the propagation
-Applications

4. Optical fibers

-Introduction

-Technological issues
-General equations of propagation
-Optical fiber models
-Guided modes in step index fibers
-Cut-off frequencies
-Weak-guidance approximation
-Recent results in fiber technology and their applications

5. Sources and detectors for telecommunications

- LEDs, Laser diodes, amplifiers
- PIN Phototiodes, avalanche photodiodes

S2-UE3: **Physics for photonics part II** Martina Knoop

Condensed matter physics

1. Introduction to the properties of solids. Crystal structures and bonding in materials. Beyond the crystalline state: soft matter (polymers, membranes, liquid crystals).
2. Momentum-space analysis and diffraction probes.
3. Lattice dynamics, phonon theory and measurements, thermal properties.
4. Electronic structure theory, classical and quantum; free, nearly-free, and tight-binding limits.
5. Electron dynamics and basic transport properties; quantum oscillations.
6. Properties and applications of semiconductors.
7. Reduced-dimensional systems.
8. Magnetism. Superconductivity.
9. Optical properties of solids.

S2-UE4: **Properties, fabrication and characterization of optoelectronic devices** Jean-Yves Natoli

- Part 1

1. Elements of semiconductors physics

- Semiconductor (bonds in SC/Crystal property/Commonly used SC/Pauli exclusion principle)
- Energy Band Description of semiconductor
- Effect of temperature on SC
- Intrinsic and Extrinsic SC
- N-type and P-Type SC
- Charge on N/P-Type SC. Majority and Minority carriers
- PN Junction: Property, polarized Junction
- Organics semiconductors

2. Basic SC Components

- PN Diode/Bipolar Transistor / MOS et CMOS Transistor

3. Electroluminescence and photoreception

Optical properties in SC (direct and indirect Gap, emission net ratio of photon)

3.1-Photoreceptor (photoelectric, photovoltaic and photoconductivity effects)

3.2-Photo emission (spontaneous and stimulated emission)

4. Fabrication of SC components

- Thin film growth and deposition

* Epitaxial growth
  * Chemical vapour deposition (CVD)
  * Physical vapour deposition (PVD)
- Etching processes
- Lithography techniques

5. Characterization techniques

- Intrinsic parameters (material properties, electronic properties)
- Extrinsic parameters (electrical properties)
- Techniques (electron microscopy, optical spectroscopy, current-voltage measurements, ellipsometry…).

S2-UE5: **Spectroscopy-The interaction of light with matter**- Thierry Angot

Elastic & Inelastic scattering

0. Surface Crystallography, 2D Bravais lattices, solid state physics and surface physics. Probing the crystallographic properties (diffraction, electron microscopy and scanning tunneling microscopy)
1. Scattering by surfaces : kinematic theory. Elementary approach: Bragg law and reciprocal spaces, 3d et 2d. Elastic scattering and (slightly) inelastic scattering, selection rules. Applications: High Resolution Electron Energy Loss Spectroscopy, Raman spectroscopy, He atom scattering, neutron scattering.
2. Classical dielectric theory. Elementary excitations in solids (surface phonons, plasmons, excitons).

Absorption and emission spectroscopies

1. Classical electromagnetic radiation : scattering, absorption and emission. Synchrotron radiation.
2. Photoemission (core level and valence band), inverse photoemission. X-ray absorption spectroscopy. Infrared spectroscopy, UV-Visible absorption. Sum-Frequency Generation spectroscopy. Photoelectron diffraction. Auger electron spectroscopy, Fluorescence.

S2-UE6: **Photon spectroscopy** Julien Duboisset Compulsory for the equivalence of the 2nd semester at KIT

This course deals with optical spectroscopy as a tool for light-matter interaction understanding, and its applications. It will introduce different spectroscopy principles and techniques, and show how they relate to biophotonics and material sciences.

1. Fundamentals

Molecular orbitals, transition dipole moments, cross sections
Electronic transitions : UV/Vis absorption, fluorescence
Vibrational spectroscopy : infrared, Raman

2. High-resolution spectroscopy

Saturated absorption, two-photon spectroscopy, Time resolved information using ultra-short pulses double-resonance techniques, ionization spectroscopy, Fourier method

3. Nonlinear spectroscopy

Nonlinear absorption, nonlinear harmonic generation
Nonlinear vibrational spectroscopy: coherent Raman techniques, sum frequency generation
Specificity of nonlinear contrasts in imaging techniques

S2-UE7: **Introduction to molecular cell biology** Manos Mavrkis/Loïc Le Goff
Compulsory for the equivalence of the 2nd semester at KIT

- Basic Chemistry
- Proteins and nucleic acids
- Gene expression
- Methods
- Evolution
- Membranes
- Energy metabolism
- Signaling
- Light microscopy
- Cytoskeleton/cell division

S2-UE8: **Advanced electromagnetics 1-Numerical approach** Gérard Tayeb

The course will be presented in the form of mixed lectures and laboratory sessions done on computers.
Some topics linked with photonics will be studied :

- Diffraction (scalar theory, Huygens-Fresnel principle, Fresnel, Fraunhofer).
- Electromagnetic scattering by a cylinder. Optical theorem, reciprocity. Resonances.
- Wavepackets
- Holography.
- Study of multilayer stacks.
- Coherence, correlation functions.

Simulations will be made in a MATLAB environment by addressing the following issues that are necessary for the computations in electromagnetics:

- Arrays, operators
- Functions
- Graphs, 2D and 3D plots
- Conditional tests
- Minimization and optimisation

S2-UE9: **Laboratory project and practice work** Frank Wagner

OSLO
AOM Modulation
EOM Modulation

Nd:YAG Laser
Laser Diode
Simulation (Diffraction)
Photometry

S2-UE10: **Nonlinear Optics** Hassan Akhouayri

Prerequiste: Linear electromagnetic optics
1. A classical model of nonlinear medium responses.
2. Classical and semi-classical results, nonlinear susceptibilities and symmetries. Nonlinear polarization, Propagation equation in nonlinear media.
3. Tree Wave Mixing: Second harmonic generation, phase matching, parametric amplification (OPA, OPO), optical rectification (THz generation).
4. Four wave mixing: Kerr Effect, SPM, Soliton propagation, Stimulated Raman effect, Phase Conjugation, Continuum generation.

S2- **Internship**

Duration: at least 7 weeks months (can be extended to 4 months) in a laboratory or in an industry.

M2 Master (2nd year) – Detailed content

S3-UE0: **Tutorials** Gérard Tayeb

The content is focused mainly on electromagnetics. It will be adjusted according to the background of the students.

S3-UE1: Introduction to **quantum optics – Applications to quantum information theory** Thomas Durt

At the beginning of the 80's, the Aspect's experiment demonstrated the violation of Bell's inequalities which ended a long quest initiated by the EPR paradox in 1935. This is a key stone for what is called nowadays the second quantum revolution. This revolution is characterized firstly by the emergence of new technologies that allowed for a constantly improved control of simple quantum systems (single and twin photon source, for example). Besides, it is based on the recognition that the irreducibly non-classical behaviour of quantum systems offers new ways to tackle old problems such as cryptography and algorithmic. This lesson aims at introducing the basic concepts behind this revolution and illustrating them with applications mostly related to quantum information processing.

Outline

Basic postulates of the quantum theory.
Black body radiation quantized harmonic oscillator coherent states, density matrix, thermal states.
Time dependent perturbation theory Fermi golden rule spontaneous emission Einstein coefficients.
Coherent states and laser light.
Entanglement quantum non-locality no signaling no cloning.
Teleportation quantum cryptography quantum computer decoherence.

S3-UE2: **Advanced electromagnetics** Frédéric Zolla/Gérard Tayeb

Part 1

4 Basics in wave packets in homogeneous media : Self-generated waves
- 4.1 Preliminary remarks
- 4.2 From constitutive relations to dispersion equation
- 4.3 Polarization of electromagnetic waves
  - 4.3.1 General considerations
  - 4.3.2 Some useful properties
  - 4.3.3 Linear and circular polarization
- 4.4 Notions of spatial wave packets
  - 4.4.1 Towards a 2D–problem
  - 4.4.2 Packets of cylindrical waves
  - 4.4.3 Packets of plane waves

5 Stratified media
- 5.1 Introduction
- 5.2 Decoupling in TE and TM waves of an arbitrary polarized incident plane wave
- 5.3 Reflection and transmission of a plane wave at a plane interface
  - 5.3.1 TE case

5.3.2 TM case
5.4 Energy considerations – Coefficients of reflection and transmission in energy
5.5 Reflection and transmission of a plane wave by a slab
5.5.1 Complex coefficients of reflection and transmission
5.5.2 A first approach of lenses
6 From Fresnel to Fraunhofer
6.1 Introduction
6.2 Fresnel transform
6.2.1 Packets of plane waves : a second approach
6.2.2 Fresnel approximation
6.3 Properties of the Fresnel transform
6.3.1 The Fresnel transform is an operator of convolution
6.3.2 Fresnel vs Fourier
6.4 A first approach of Fraunhofer optics : Fresnel at "infinite" distance
6.4.1 A second approach of Fraunhofer optics : Fresnel optics in using a convergent thin lens

Part 2

In the second part of UE2 we illustrate the problem of the scattering of electromagnetic fields in the simple case of the diffraction by a cylinder. Some classical methods of resolution are explained (modal decomposition, integral method, fictitious sources method). We highlight some basic concepts such as reciprocity or concepts related to energy, such as the optical theorem. A numerical implementation of the solution will be conducted, with application to the study of the resonances of the structure.

S3-UE3: **Laser sources and applications/matter interaction** Nicolas Sanner, Jean-Yves Natoli, Frank Wagner

Part 1: Advanced laser sources

- Short and ultrashort laser sources: Starting from the knowledge acquired with S1-UE2, the thorough presentation of both concepts and technical issues for generating short and ultrashort pulsed laser source will be presented.
- Beam manipulation: How to handle, propagate, and even shape a laser beam and or/a laser pulse ?

Part 2: Optical properties of solids

The basis of laser-matter interaction

- Optical coefficients
- The dielectric function $\varepsilon(\omega)$ and the complex refractive index
- Drude and Lorentz models
- Nonlinear properties (complementary with S3-UE1: "Nonlinear optics)

Part 3: Laser-matter interaction in pulsed regime

- Physical mechanisms and timescales
- From absorption to ablation
- Specificities of interaction: nanosecond to femtosecond regime

Part 4: Examples of applications

Laser = a tool for…

- Analysis: nonlinear microscopy, pump-probe, LIBS…
- Material modification/cleaning/structuration/processing/surgery…
- High intensities applications/facilities: LMJ/NIF, FEL, X-rays, protontherapy…

S3-UE4: **Optical components and optoelectronics** Frank Wagner/Guillaume Demésy/Frédéric Lemarquis/Julien Lumeau

Topic 1: Thin-Film Optical Filters

- Introduction to thin-film optical filters, Fresnel coefficients and matrix formalism
- Presentation of optical functions and stacks design
- Experimental demonstration of thin-film optical filters fabrication and spectroscopic characterization
- Refractive index determination and reverse engineering

Topic 2: Crystal-based optical components

- Optics in anisotropic media : uniaxial and biaxial birefringence, how to find the polarizations and refractive indices corresponding to a given propagation direction
- Wave plates
- Polarizers
- Electro-optic modulators
- Acousto-optic modulators
- ? Focusing problems in birefringent media?

Topic 3: LED/OLED based lightning and displays

- Prerequisites/Introduction
    - Solid state physics
        - Spontaneous emission
        - Doped semiconductors
        - Inorganic Light Emission Diodes
    - Radiometric aspects of LED-emitted light
- Organic Light Emission Diodes
    - Chemical synthesis of organic semiconductors
    - Light generation
    - Carrier transport
- OLED matrix displays
    - History and basic principles of display devices families
    - OLED active matrix
    - Opening remarks: sensors and displays

Topic4: Optical components

Optical fibers, polarizers, birefringent plates, detectors, sources

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S3-UE5: **Photonics for biomedical applications** Anabela Dasilva/Sophie Brasselet

1- **Optical imaging in biological media**

1a. From single molecules to cell scale : fluorescence and super-resolution

techniques
- Fluorescence and single molecule

- Fluorescence microscopy techniques (confocal scanning, wide field, TIRF)
- super-resolution below the diffraction limit.
1b. From cells to tissues and in vivo imaging
- Depth penetration in biological tissues.
- Going deeper with adaptive optics.
- label free techniques : coherent non linear processes (second harmonic generation, third harmonic generation, Coherent Raman scattering)

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2- **Diffuse optical techniques**
- Modelling light propagation through biological tissues
- weakly diffusing tissue: OCT, polarization gating imaging, Speckles contrast imaging
- Probing tissue in depth: Imaging techniques based on Diffuse Optical Spectroscopy and Tomography

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S3-UE6: **Advanced methods for optical instrumentation** Benoit Epinat

Pre-requisites

- Optical geometry basis: ray-tracing, conjugation furmulae (dioptre, thin lens, mirrors), definition of an optical system (field of view, pupil, cardinal points)
- Basic use of ray tracing / optimisation / optical design software, e.g. OSLO
- Fourier optics basis (diffraction, Fresnel approximation, Fourier transform)
- Black body laws

1. Advanced Optical Design I
    - Aberrations.
        - Wave aberration, axial and transverse aberrations, chromatism, spherical aberration, astigmatism/curvature, distortion, coma, Seidel, Zernike.
        - Aberrations and Fourier optics: point spread function, Strehl ratio, Rayleigh and Marechal criteria
    - Performances.
        - Computing power of an optical system and detection limits based on optical performance.
    - Optimization
        - Optimization of materials: material selection, optical surface treatment
        - Optimization of surfaces: diopters, mirrors
        - Optimization software (e.g. Oslo, Zemax)
    - Photometry / Radiometry.
        - Definitions and relationships between quantities
        - Energetic quantities (e.g. flux, intensity, luminance)
        - Luminosity quantities (e.g. photonic, spectral)
        - Applications (e.g. metrology, telemetry)
2. Dispersive spectrography and Interferometry. Component analysis (9 hours)
    - The principle of spectrometry

- The prism spectrometers
- Useful diffraction gratings and GRISM
  Blazing, Elbert configuration, Littrow and non-Littrow - configuration, Echelle, Cross-dispersed echelles, Volume Phase Holographic gratings
- Slit-limited resolving power
- Interferences, spatial and temporal coherence
- Fourier Transform spectrometers
- Fabry-Perot interferometers
- Interferences and application (e.g. optical surface control)
- Multiple beam interferometry

S3-UE7: **Nanophotonics** Stefan Enoch/Nicolas Bonod

Nanophotonics is the study of the light interactions with objects at the nanometer scale. We will introduce the field of nanophotonics and the undelying motivations.

A - Plasmonics and nanoantennas.

In this part of the course, we will study how light can resonantly interact with photonic nanostructures. The excitation of electromagnetic resonances in photonic nanostructures leads to important enhancements of electromagnetic field intensities and strongly modify their optical properties; with important applications ranging from biosensing to solar energy.

1. Surface plasmon polaritons on flat and structured metallic films
   Fresnel coefficient, Brewster incidence, existence of poles and zeros.
   Excitation with plane waves
   Applications
2. Surface plasmons and Mie resonances in metallic nanoparticles
   Effective polarizability of a spherical particle, existence of poles and zeros
   Scattering and extinction cross-sections
   Modification of the spontaneous emission
   Applications

B - Periodic media – Photonic crystals

1. Introduction: Maxwell operator spectrum
2. Photonic crystal modes
   Direct and reciprocal lattices
   Direct and inverse Wannier transforms
   Bloch modes
   Dispersion relation and group velocity
   Methods (Finite Elements FEM, Plane wave PWM)
3. The 1D scalar case thoroughly
4. Examples : PCs in Nature, Microstructured optical fibers, a word about homogeization

C- Metamaterials and transformation optics.

Metamaterials and transfomation optics have been recent breakthrough in photonics. Transformation optics is based on coordinates transformations and allows to bend light at will. While metamaterials refer to composite materials that posses one or several properties that cannot be found in nature. The combination of both constitutes a highly topical fields in naophotonics.

1. Metamaterials. Concepts and examples of metamaterials (nead zero optical index, double negative metamaterial, hyperbolic metamaterial...)
2. Transfomation optics. Basic principles, example: perfect lenses and external cloaking, Invisibility..

S3–UE 8: **Numerical Methods in Electrodynamics** Gilles Renversez/Kamal Belkebir

Part I: Direct methods in computational photonics - Some theoretical results and test examples

Pre-requisites
Guided optics
Basics of integration theory (integration by parts)
Basics of numerical analysis (discretization, finite difference)

This lecture will contain both numerical demonstration realized by the teacher and training classes for the students using dedicated softwares (Gmsh/GetDP for the Finite Element Methods, Meep for the FD-TD, and MPB for the Plane Wave Method)

1. Introduction : motivations, possible classifications of the methods, brief historical survey, general remarks on high performance computing
2. Operator point of view, symmetry properties in electrodynamics and their use in numerical modelling
3. Finite Element Method and introduction to Gmsh/GetDP softwares
   - Basic principles with one dimensional case and the Helmholtz equation : analytical results versus numerical ones
   - Few words on the Galerkin method and the boundary conditions
   - Domain discretization and interpolating functions
   - From classical Maxwell equations to their weak formulation
   - Eigenvalue problems in the harmonic regime (modal analysis): examples from Guided Optics lecture (slab, optical fiber)
   - Survey of more advanced topics : outgoing wave condition and perfect matching layers, periodicity, vector field and 3D case, …
4. FD-TD and introduction to Meep software (3h+1,5h de TP)
   - Yee cell
   - Courant–Friedrichs–Lewy (CFL) condition applied to FD-TD
   - Principle of equivalence and its practical use to implement sources
   - Material dispersion
   - Simple examples : comparison between time-domain and modal approaches, third harmonic generation in simple waveguide
5. Plane Wave Method and introduction to MPB software (3h+1,5h)
   - Harmonic regime and eigenvalue problem
   - Periodic structures and Floquet-Bloch theorem
   - General plane wave method (E and H methods)

-Know extension : supercell method
-Simple examples with MPB : dispersion curves and band diagram for 1D case and 2D case, band gap, supercell technic and defect

Part II: Electromagnetic inverse scattering problem

1. Introduction and statement of the electromagnetic inverse scattering problem
2. Direct solutions under the Born Approximation
3. Iterative solutions : linearized and non linearized approches
   -Newton-Kantorovitch method
   -Distorted Wave Born method
   -Analytic equivalence between NK and DWB
4. -Gradient and Modified gradient methods

S3-UE9: **Instrumentation for astronomy from ground to space** Philippe Amram

1. Observing techniques to collect photons from space and ground-based telescopes
   - From science goals to instrumental techniques requirements
   - Space and ground-based instrumentation and applications
     Overview on Gamma ray, x-ray, ultraviolet, visible, infrared, microwave and radio telescopes
   - Detectors
2. Advanced Optical Design II
   - Optimization
     - Optimization of materials: material selection, optical surface treatment
     - Optimization of surfaces: diopters, mirrors
     - Optimization software (e.g. Oslo, Zemax)
3. Spectral analysis (optical, UV and IR wavelengths, system analysis - 8 hours)
   - Dispersive spectroscopy
   - Spectro-imagery
   - Fourier transform spectroscopy
   - Multi-object spectroscopy
4. Active and adaptive optics (visible and IR wavelengths, system analysis - 6 hours)
   - Active technics. Fabrication of optical components by elastic constrains. Compensation of optical aberrations.
   - Adaptive technics. Description, sizing and reconstruction technics.
   - Wavefront analysis. Concepts and examples (e.g. Shack-Hartmann).
5. Coronography. Application of Fourier Optics, (2 hours).
   - Extrasolar planet science goals
   - From Huygens' wavelets to Fraunhofer approximation and Fourier formalism. Fourier relations: pupil and image
   - Phase, band-limited, notch-filter, discrete, continuous, apodized masks
   - Perturbation: ripples and speckles
6. Space environment & Space technology (3 hours)
   - Space Environment (vacuum, radiation and plasma). Effects on components, technologies and missions. Vibration and shock onboard a

rocket. Maintenance-free operation. Test levels and condition before launch.

- Space Systems Engineering. Mission analysis and design. System design approach. System engineering process and methodology. Functional analysis techniques. Optical, mechanical, thermic and electronics performances and coordination.
- Management for space development. Conception, development, operations and exploitation of a space instrument.

S3-UE10 & 11: **Experimental projects A & B**

The students must choose the projects in order to reach a total of 0, 4 or 8 points in the following list.

For 0 points, the corresponding ECTS will be 0. For 4 points, the corresponding ECTS will be 3 (S3-UE 10/S3 UE 11). For 8 points, the corresponding ECTS will be 6 (S3-UE 10 and S3 UE 11)

1 - Determining optical properties of biological tissues (counts for 2 points) - Anabela Dasilva – Institut Fresnel

The labwork consists in applying photon migration models, described in the biophotonic course, for determining the absorption and reduced scattering coefficients of biological tissues. As a preliminary work, the students will have to read a publication on the subject. Measurements will be performed on phantoms that are media mimicking the optical properties of common tissues. The measurements will be fitted to a mathematical model to provide the results.

2 - Optical Autocorrelation : how to estimate the monochromaticity of laser light ? (counts for 2 points) - Gaétan Hagel – PIIM Laboratory

This experimental project is devoted to the study of the "monochromaticity" of laser light. Indeed, if the laser radiation is often presented as monochromatic, the experimental characterization of this particular aspect is very rare.
In this project, the students will reproduce a research experience described here (*Novel method for high resolution of laser output spectrum*, Okoshi et al, Electron. Lett. **Vol 16,** p.630, 1980) where the main idea is to compare the spectrum of the laser light at two different instants of time to deduce the space-time fluctuations of laser light by autocorrelation.
During this project, students will have to prepare and realize the experiment (based on the beat signal of two laser paths, where one is frequency-shifted by acousto-optic modulation and propagated in a long optical fiber). They will record measurements and analyze them in regards to the corresponding theory.

3 - Numerical experiments in photonics with the Finite Element Method (counts for 2 points) - Guillaume Demésy, Gilles Renversez – Institut Fresnel

Comprehensive examples in several fields of photonics are studied in this project through several numerical experiments based on the finite element method.

-Basic 2D examples to compute the electromagnetic diffraction pattern obtained with simple objects under plane wave or gaussian beam illumination.

-Kretschmann-Raether set-up and plasmon excitation in 2D

-Modal approach (eigenvalue problem) in 1D and 2D : applications to classical waveguides (slab, fiber, ...)

-Periodic structures and boundary conditions : applications to photonic crystal and their dispersion relation

-Diffraction by finite size photonic crystals

-Simple 3D examples (*e.g.* diffraction by a single sphere)

Each student will work with a provided computer and the needed software tools consequently the maximum number of students for this project is set to 8. The project is divided in two four hours parts.

4 - Holographic diffaction grating for emission spectroscopy (counts for 1 point) - Alexandre Escarguel – PIIM Laboratory

Emission spectroscopy is one of the most used diagnostics in research and industry. It has the advantage to be non invasive. The diffraction grating is the main element of such diagnostics and is essentially characterized by the lines number/mm "ng". for low values of ng, mechanical ruling can be used. However, for ng larger than 1800 lines/mm, it is necessary to use holographic techniques.

This project proposes to create a holographic diffraction grating that will be the centerpiece of a transmission spectrometer. Having familiarized with the principles of holography, the students will realize and qualify a holographic diffraction grating with a laser and use it to mount an emission spectrometer.

5 - Virtual Instrumentation (Labview) (counts for 2 points) - Jofre Gutierrez – LAM Laboratory

LabVIEW is a programming language developed by National Instruments (NI). Its main characteristics are the tight integration with the hardware developed by NI and the creation of Graphical User Interfaces (GUI). While it can be used as a generic programming language, the two mentioned aspects have make it the choice of preference of industry and research for doing data acquisition and control.

The two days practical laboratory work, are organized as follows. The first day will be dedicated to learn the programming aspects of the language as well as how to create GUI. In the second day we will perform data acquisition and analysis using NI hardware and LabVIEW

6 - Integral Field Spectrograph (counts for 2 points) – Benoit Epinat – LAM Laboratory

An integral field spectrograph (IFS) is an optical instrument combining spectrographic and imaging capabilities, used to obtain spatially resolved spectra in astronomy and other fields of application such as bio-medical science and earth observation or remote sensing (Archeology).

IFS has become a very important technique of astronomy with the proliferation of large telescopes where there is a need to study the spectra of extended objects as a function of position, or of clusters of many discrete stars or point sources in a small field. The students will

- Work on an optical bench in order to construct three IFS designed for astrophysical purposes and understand their specificities and fields of application.
- Learn basics of optical design of a spectrograph (collimator associated to a camera lens), and how to use Fabry-Perot technique, or micro-lens array coupled with a grism (Prism+Grating) to obtain both an imaging and a spectroscopic system.
- Manipulate various optical systems, electronics (camera detector) and informatics (to pilot the camera) to build these spectrographs. They will deal with light dispersion (GRISM), interferences (Fabry-Perot) and field-pupil inversion (through the micro-lens array). All these notions will be coupled in a final optical assembly.
- Use these spectrographs to conduct a spectral analysis of various light sources (spectral lamps, continuum lamp) and see how each spectrograph can be wavelength calibrated.
- Study the quality of spectral and spatial information separation in these spectrographs and their transfer functions.

7 - Stellar Coronography (counts for 1 points) – Olivier Fauvarge – LAM Laboratory

Exoplanets orbiting around a star could be one billion times fainter than the star itself, the exoplanets light is by consequence hidden in the star's bright glare.
A coronagraph is a telescopic attachment designed to block out the direct light from a star so that nearby objects (typically exoplanets) can be resolved. They are being used to find extrasolar planets and circumstellar disks around nearby stars.
The students will :

- Work on an optical bench in order to construct a coronograph.
- Learn the history of the coronography and the futures challenges of the stellar coronography.
- Learn basics of optic design of the Lyot coronagraph through geometrical and diffractive interpretations of its optic elements (namely the Lyot mask and the Lyot stop).
- Have knowledge of the other coronographs.
- Use numerical simulations codes to: 1° Understand the architecture of a simulation code of an optic system using Fraunhofer diffraction. 2° Compare the efficiency of the existing coronographs.
- Build a Roddier coronagraph (using lens, masks, light source, CCD camera) on an optical bench and use it in order to test the influence of the diverse optical parameters (namely the sizes of the Roddier mask and the Lyot stop) on the fundamental criterion of the coronography that is the extinction capacity.

8 - Adaptive Optics (counts for 1 point) - Kacem El Hadi - LAM Laboratory

The imaging of astrophysical objects from ground telescopes is severely disrupted by the effect of the atmospheric turbulence (refractive index change due to movements of air masses). This turbulent medium effect induces wavefront distorsions, which reduces the capacity of ground instruments to distinguish two close objects, their angular resolution.

Adaptive Optics (AO) is a technique allowing to reduce this effect in order to improve the performance of optical systems and, then, to find the ideal resolution of a telescope.

Although developed for astronomy, the adaptive optics is widely used in other domains today such as retina imaging in ophthalmology, microscopy or still laser beam shaping.

The students will

- Work on an optical bench in order to analyze the effect of turbulent medium on images.
- Tackle the AO working principle and calibration systems
- Understand the role of the three main elements of an AO system:
  - The wavefront sensor (WFS) for wavefront aberration measurements.
  - The deformable Mirror (DM) for wavefront correction.
  - The Real Time Computer (RTC) for control and optimization of the wavefront measurement-correction process
- Analyse the impact of pupil size relation on the resolution
- Operate the AO system in opened and close loop and measure the gain.

9 - PROJECTS AT OHP (count for 3 points)

The following three projects are located at the OHP (Observatoire de Haute Provence), they constitute a non-breaking block of 3 points.

Interferometric Observations at OHP (T80) - Hervé Le Coroller

An astronomical interferometer is an array of telescopes or mirror segments acting together to probe structures with very high resolution.

Interferometric observations are widely used for modern optical astronomy, infrared astronomy, submillimetre and radio astronomy, they provides the ability to study celestial objects in unprecedented detail.

The students will:

- Use the telescope of 80 cm of diameter (T80) located at the OHP to observe planets of our solar system;
- Mimic a real interferometer in positioning a 2-holed mask in front of the T80. This will allow forming fringes on the detector when observing bright stars or planets as Saturn or Jupiter;
- Study the angular separation capability of the interferometer in varying the distance between the two holes;
- Measure the diameter of selected planets of our solar system (ex: Venus, Mars, Jupiter, etc) in analyzing the visibilities of the fringes;

Learn all the steps of the reduction of interferometric data. This pedagogic exercise allows the students to understand how works a real interferometer like the VLTI, CHARA, etc.

Imaging and spectroscopic observations at OHP (T120) – Christophe Adami

Astronomy is an observational science, it first consists of recording data in order to find out the measurable implications of astrophysical models and theories.

Starting from general scientific questions, this project aims to discover imaging, photometric and spectroscopic observational techniques.
The students will

- Learn in a professional context
  - how to plan an observation to tackle a scientific question,
  - how to choose objects adapted to the instrumentation at disposal,
  - how to plan their observations during the night;
- Perform these observations during the nights. Well known astronomical objects as star clusters, double stars, clusters of galaxies, supernovae remnants, dying stars, regions of star formations, … will be observed with an imager than with a spectrograph.
- Analyze the collected data in order to extract the information and interpret them in the frame of a model.

Characterization of a CCD - Hervé Le Coroller & Christophe Adami

A charge-coupled device (CCD) is an integrated circuit etched onto a silicon surface forming light sensitive elements called pixels. Photons incident on this surface generate charge that can be read by electronics and turned into a digital copy of the light patterns falling on the device.
CCD are major piece of technology in modern digital imaging. CCDs come in a wide variety of sizes and types and are used in many applications from cell phone cameras to high-end scientific applications; they are widely used in professional, medical, and scientific applications where high-quality image data is required, as for instance in astrophysics. In this regard the CCD camera response needs to be adequately characterized.
The students will:

- Work on a specialized bench in order to characterize CCD and understand their specificities and fields of application.
- Use integrating spheres in order to perfectly control the incoming light source and, by the way, study the operation of a professional integrating sphere.
- Learn and apply the basics techniques to characterize CCD imaging detectors. The main goals are to master the steps in any instrumental project involving imaging capture.
- Characterize "unknown" CCDs by illuminating them with various sources in order to quantify their characteristics in terms of sensibility, wavelength response, noises levels, exposure time linearity, instrumental performances, environment (temperature…)

S4- **Thesis**

Duration: 6 months in a laboratory or in an industry.
Evaluation: at the end of the Master thesis the students have to write a report and do a presentation (defense: 20 minutes+10 minutes for the questions). The Master thesis is evaluated by a jury on the quality of the presentation (1/3), on the quality of the report (1/3), on the evaluation of the supervisor (1/3).
