UNIVERSITÀ
DEGLI STUDI DI MILANO-BICOCCA

COURSE SYLLABUS

Materials Spectroscopy and Microscopy

2526-1-FSM02Q003

Aims

The course aims to lead students towards an understanding of the fundamental concepts in two main areas of materials science:
i) optical spectroscopy, i.e. the study of the response of materials to electromagnetic radiation, including implications for applications in photonics, optoelectronics and fiber optic communications;
ii) microscopy, of which the fundamental principles and the main techniques for the study of the infinitesimally small will be investigated through methods based on light-matter interaction, electron-matter interaction, and scanning probe approaches.

At the successful completion of the course, the student will have developed a solid understanding of the fundamental principles governing the propagation of light in various media (knowledge and understanding), as well as of the interface and local scale phenomena that form the basis for the study and implementation of experimental techniques (applying knowledge and understanding). The student will be able to critically assess and select the most appropriate spectroscopic and/or microscopic methods for carrying out basic measurements (making judgements), and will be proficient in employing precise and rigorous scientific language to effectively communicate the acquired knowledge (communication skills).

Although the major emphasis is put onto the physical aspects, the course fosters the development of cross-disciplinary ablilities, directly connected with other scientific areas, including, e.g., biophysics and biomaterials. During the course, students are required to play a pro-active role in discussing topics of their interest. Students will gain specific skills in the cross-disciplinary approach to materials that, starting from the fundamental physical basis, leads to emerging applications at the state-of-the-art (learning skills).

Contents

The course addresses the fields of:
i) optical spectroscopy, intended as the study of the interactions between electromagnetic radiation and materials,

considering both fundamental concepts and its very extended applications;
and
ii) microscopy, mainly focused on light-based, electron-based and scanning probe methods.

Fundamental aspects of spectroscopy and microscopy are treated alongside the experimental approaches that can be adopted. Classical techniques and advanced methods are proposed both during lessons and during the analysis of case studies. Students will acquire solid competences and skills in such topics, becoming able to apply them also in cross-disciplinary contexts.

The course is composed of three different parts:

Part A: Optical Spectroscopy: Fundamentals
A1- Dielectric response of solids
A2. Interfaces and films

Part B: Optical Spectroscopy: Applications
B1. Investigations of Materials through resonance phenomena
B2. Introduction to non-linear response of materials to electromagnetic radiation
B3. Light spectroscopy of disordered media
B4. Photonic band-gap structures and metamaterials

Part C: Fundamentals and Applications of Microscopies
C1. Light Microscopies
C2. Electron Microscopies
C3. Scanning Probe Microscopies

Detailed program

Part A: Optical Spectroscopy: Fundamentals

A1- Dielectric response of solids
Review of Maxwell's equations in vacuum and in matter; wave equation; the electromagnetic spectrum. Propagation of light in materials; complex dielectric function and refractive index; reflectance, transmittance, and absorbance. Dielectric tensor and anisotropy; wave equation in anisotropic media.Microscopic origin of dielectric response: Lorentz and Drude models; dispersion relations and Kramers-Kronig relations. Screening effects and local field corrections, Lorentz-Lorenz and Clausius-Mossotti relations. Cauchy and Sellmeier models. Semi-classical model of the dielectric response. Dielectric behavior of insulators, metals, and semiconductors.

A2. Dielectric response of interfaces and films
Introduction to interfaces; Fresnel coefficients; transmittance and reflectance at normal incidence; Brewster angle. Total internal reflection and evanescent waves.
Thick slabs and thin films: transparent and absorbing films; films on substrates. Multiple interfaces, multilayer structures, and the transfer matrix method.

Part B: Optical Spectroscopy: Applications

B1- Investigations of Materials through resonance phenomena
Interaction of light with matter: absorption, spontaneous emission and stimulated emission. Principles of lasers (four-level system, population inversion, critical threshold, rate-equation model). Optical absorption and reflectivity measurements. Luminescence (fundamentals, quantum efficiency, Anti-Stokes). Time resolved luminescence and fluorescence. Time-correlated single-photon counting. Time-resolved Emission. Time-resolved Optical Pump-Probe. Raman Spectroscopy.

B2- Introduction to non-linear response of materials to electromagnetic radiation
Fundamentals of the non-linear response; Second and third order non linearity; Electro-optic and Kerr effects; Origin of non-linearity in materials (crystals, glasses, polymers). Impedance spectroscopy.

B3- Light spectroscopy of disordered media
Glass materials engineering; wave propagation in layered dielectrics; from Fresnel coefficients to transfer matrix and scattering matrix; amorphous dielectrics in optical technology; quantifying and controlling structural disorder (diffraction and light scattering techniques); effects of disorder on the energy gap and transitions at localized states; spectroscopy of transition metal ions and rare earth ions in glass-based materials.

B4- Photonic band-gap structures and metamaterials
Bragg interference in planar and non-planar structures, transmission and reflection, occurrence of a photonic band-gap. Survey of photonic band-gap nanostructures in one and two dimensions. Examples of applications: photonic crystal fibers and super-continuum generation, waveguides and photonic components, optical spectroscopies, laser cavities.
Basics of metamaterials: tuning the e.m. properties of a system through structural engineering, control of the magnetic permeability, single and double negative materials, negative refractive index; open possibilities and perspective applications of metamaterials in different fields.

Part C: Fundamentals and Applications of Microscopies

C1- Light Microscopy
Basic principles of geometric optics; Light diffraction and Abbe theory of imaging; Design and layout of a light microscope; Fluorescence microscopy and Confocal microscopy; Beyond the Abbe limit: structured-illumination microscopy (STED); Super-resolution microscopy: PALM and STORM.

C2- Electron Microscopy
Wave-nature of electrons and basic principles of electron optics; Interaction between electron and matter.
Transmission Electron Microscopy (TEM): Layout of a TEM microscope; Imaging modes (bright and dark field), diffraction and crystallography; Amplitude, diffraction, and phase contrasts in TEM; High-Resolution TEM; Scanning TEM; TEM sample preparation.
Scanning Electron Microscopy (SEM): Layout of a SEM microscope; Secondary electron contrast and imaging modes.
Analytical Electron Spectroscopies in SEM and TEM: Energy-Dispersive X-Ray spectroscopy (EDX); Electron Energy Loss Spectroscopy (EELS); Auger Electron Microscopy (AEM); Cathodoluminescence (CL).

C3- Scanning Probe Microscopy
General concepts on scanning probe techniques; Scanning Tunnelling Microscopy: tunnelling phenomenon, detection methods, imaging modes, and spectroscopic capabilities. Atomic Force Microscopy: Tip-sample forces and piezo-electric scanners; cantilevers, detection methods, and imaging modes. Optical near-fields and SNOM. Tip-Enhanced Raman Spectroscopy (TERS).

Prerequisites

Fundamentals of classical electromagnetism and of structure of matter (topics presented in the Bachelor of Science in Materials Science).

Teaching form

The course includes both theorethical lectures where the basic principles of the various topics covered will be defined, and practical exercises where specific case studies, experimental methods and applications will be discussed, as well as visit to laboratories of interest in small groups.
In particular, the following activities are planned:

- 24 hours on part A (Optical spectroscopy: fundamentals) carried out in person (delivered didactics).
- 32 hours on part B (Optical spectroscopy: applications), including both lectures carried out in person (delivered didactics), and visits to laboratories of interest (interactive didactics).
- 36 hours on part C (Fundamentals and applications of microscopy), including both lectures carried out in person (delivered didactics), and visits to laboratories of interest (interactive didactics).

Textbook and teaching resource

1. J. Peatross and M. Ware, Physics of Light and Optics (2015), available at optics.byu.edu
2. O. Stenzel, The Physics of Thin Film Optical Spectra (Springer, 2005)
3. G. Giusfredi, Manuale di ottica (Springer, 2015)
4. E. Hecht, Optics (Addison Wesley, 2002)
5. M. Born and E. Wolf, Principles of Optics (Pergamon Press, 1989)
6. F. Wooten, Optical Properties of Solids (Academic Press, 1972)
7. J. G. Solé, L.E. Bausà, D. Jaque, "*Optical spectroscopy of Inorganic Solids*", Wiley
8. B.E.A. Saleh and M.C. Teich, "*Fundamentals of Photonics*", Wiley
9. R. Feynman, *"Lectures on Physics*" vol. 1, part 2, Inter European Editions
10. K.S. Potter, J.H. Simmons, Optical Materials, Elsevier, 3rd chapter
11. Svelto, Orazio. Principles of Lasers. New York: Springer, 2010.
12. J.D. Joannopoulos, R.D. Meade, J.N. Winn, "Photonic Crystals", Princeton University Press
13. F. Costa and M. Borgese, "Metamaterials, metasurfaces and applications," in Compendium on Electromagnetic Analysis. Singapore: World Scientific, 2020, ch. 3, pp. 89–169.
14. D. B. Murphy, Fundamentals of Light Microscopy and Electronic Imaging, 1st Edition; Wiley-Liss, 2001.
15. D. B. Williams and C. B. Carter, Transmission Electron Microscopy; Springer, 2009.
16. R. F. Egerton, Physical Principles of Electron Microscopy: An introduction to TEM, SEM, AEM; Springer, 2008.
17. E. Meyer, H. J. Hug, R. Bennewitz, Scanning Probe Microscopy: The Lab on a Tip; Springer, 2003.

Additional resources:
Slides provided by the professors. Specific scientific papers, tables, and diagrams, are available on the e-learning platform.

NOTE: textbooks 2 and 3 can be downloaded as pdf files from the library website; textbook 1 is also freely available.

Semester

The course has an annual duration. Lessons of Part-A are given in the first semester, together with a portion of Part B. The remaining of Part-B and the whole Part C are given in the second semester.

Assessment method

a) In itinere tests
The course includes two in itinere tests, one at the end of the first semester and one at the end of the second semester. The two in itinere tests will include a written test with some open-ended questions on the topics covered in the first and second semester, respectively, followed by a short oral interview.

b) Final exam
For students who do not wish to take the in itinere tests, a full exam is scheduled at the end of the second semester consisting of a written test with some open-ended questions, followed by a short oral interview

c) Assessed skills
The following skills are assessed in the in itinere tests and in the final exam:

1. describe the dielectric response of the main classes of materials and identify the response requirements to electromagnetic radiation necessary for a material to be suitable for specific functions;
2. Design measurement strategies for the spectroscopic and microscopic characterization of the properties of materials in relation to their applications.

d) Evaluation criteria
Both in the written tests and in the oral interviews, the following parameters are evaluated:
i) percentage of the proposed questions to which the correct answer is given;
ii) for each answer, percentage of experimental and theoretical details provided by the student compared to those exposed, discussed and applied during the course;
iii) for each topic proposed during the test, percentage of comments on the applicative aspects compared to those discussed and included in the contents of the program.

For those who will take the two in itinere tests, the final evaluation will be given by the average of the evaluations achieved in the two tests, each according to all the criteria indicated above.

Office hours

8 - 18

Appointments between professors and students should be agreed via e-mail.

Sustainable Development Goals

QUALITY EDUCATION | INDUSTRY, INNOVATION AND INFRASTRUCTURE | RESPONSIBLE CONSUMPTION AND PRODUCTION