PHYSICS OF HOMOGENEOUS AND NANOSTRUCTURED DIELECTRICS

Master in Sustainable Materials

CONTACT INFORMATION

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COURSE CONTENT AND INTENDED LEARNING OUTCOMES (ILOs):

The course gives the fundamental tools for understanding the electromagnetic response of optical dielectric materials – specifically concerning the applications in photonics, fiber optics, and optoelectronics – with a particular focus on the role of structure, nanostructures, and short- and long-range order of the material on the intrinsic electronic and phononic transitions, as well as on the localized transitions responsible for optical absorption and light emission of optically active ions.

At the end of the course, the student will be able to

- tailor structural features and compositional doping of dielectric materials for specific optical response.
- design possible strategies for functionalizing optical materials by suitable processes able to modify the material structure and the local coordination of optically active species
- use structural design and functionalization processes for developing sustainable strategies of substitution or reduction of critical materials in light-emitting optical devices.

Aligning with the EIT OLOs:

1 = peripherally relevant to the course content; 2 = highly relevant to course content.

- ☑ EIT OLO 1 - Making value judgments and sustainability competencies – 1
- ☐ EIT OLO 2 - Entrepreneurship skills and competencies
- ☑ EIT OLO 3 - Creativity skills and competencies - 2
- ☑ EIT OLO 4 - Innovation skills and competencies - 1
- ☑ EIT OLO 5 - Research skills and competencies - 2
- ☐ EIT OLO 6 - Intellectual transforming skills and competencies
- ☑ EIT OLO 7 - Leadership skills and competencies - 1

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

Description of <u>how</u> the course covers the EIT OLO(s) and EIT Thematic Areas

The course combines lectures with a set of interactive group activities which propose technological targets – not explicitly presented during the lectures – stimulating the creative merging of different topics and previously acquired competences (**OLO 3**, **OLO 4**). The proposed technological target is chosen so as to represent an application in cross-disciplinary areas, inviting students with different background – with degree in Physics, Chemistry, Engineering, or Biosciences – to interact to each other (**OLO 5**). Group activities are also intended to train students at sharing and leading ideas and decisions within the working team (**OLO 7**). During the interactive work, students focus their attention – with the guidance of the teacher and the acquired knowledge on critical raw materials – on sustainable technological solutions, evaluating substitution or reduction of critical elements (**OLO 1**). According to the latter topic, the course falls into the **EIT Thematic Area No. 5**: "Substitution of critical and toxic materials in products and for optimal performance".

ASSESSMENT METHODS AND GRADING SYSTEM

The final assessment is based on an interview in which different student abilities are evaluated.

- During the assessment, the student must demonstrate to know the main principles for the description of the electromagnetic response of dielectrics (*content-based assessment*),
- The student must also show how the acquired knowledge can be used as a tool for the analysis and the design of optical functions of technological relevance starting from structure, composition, and functionalizing treatments (*competence-based assessment*, also evaluating **OLO 4**).
- Part of the assessment comprises the analysis of an example of material system, so as to allow the student to demonstrate skills in applying the acquired knowledge for solving a real technological problem according to a sustainable strategy (*impact-based assessment*, also evaluating **OLO 3** and **OLO 1**).
- In the final discussion, within the assessment, the student is asked to reconsider and reanalyze some tasks of the interactive group activities, giving a personal view of feasibility of results and methods (*competence-based* and *impact-based assessment*, evaluating **OLO 5** and **OLO 7**).

The grades in the Italian university system are expressed out of **30.** The passing grade is **18/30**.

An example of the breakdown of a hypothetical final grade:

ASSESSMENT METHOD	WEIGHT ON FINAL GRADE
Class participation	0%
Group task	0%
Written output(s) (essay, position papers, case study, final exam etc.)	0%
Oral exam (including discussion on Group tasks and on possible intermediate written tests of self-assessment on knowlwdge and skills)	100%

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COURSE SESSIONS

Session 1	INTRODUCTION TO THE COURSE DIELECTRIC RESPONSE TO ELECTROMAGNETIC WAVES
Content	• Introduction to the course • Background of electromagnetism
Readings	K. S. Potter, J. H. Simmons, Optical Materials, Elsevier Science Publishing Co Inc, 2021. Chapter 1 O. Stenzel, The physics of thin film optical spectra, Springer, 2016.
Content	• Electromagnetic waves, dipoles and polarization • Boundary conditions and light speed reduction
Readings	M. B. James, D. J. Griffiths, Why the speed of light is reduced in a transparent medium, Am. J. Phys. 60, 309 (1992).
Content	• Link between light speed reduction and intensity attenuation • Kramers-Kronig relations between dispersion and dissipation • Dependence of the refractive index on material and external factors • Clausius-Mossotti and Lorenz-Lorentz equations
Readings	K. S. Potter, J. H. Simmons, Optical Materials, Elsevier Science Publishing Co Inc, 2021. Chapter 3 D. B. Tanner, Optical effects in solids, Cambridge University Press, 2019. Chapter 9
Assignment	Multiple-Choice knowledge Test

Session 2	REFRACTIVE INDEX PARAMETRIC DEPENDENCES AS A TOOL FOR MATERIAL FUNCTIONALIZATION
Content	• Generalized equation for n vs. molar polarizability and volume • Fiber Bragg gratings – fundamentals • Fiber Bragg gratings - applications • UV Photosensitivity & refractive index changes
Readings	A. Othonos, K. Kalli, Fiber Bragg Gratings: Fundamentals and Applications in Telecommunications and Sensing, Artech House Optoelectronics Library, 1999. Chapter 1 B. Poumellec, F. Kherbouche, The photorefractive Bragg gratings in the fibers for telecommunications, J. Phys. III France 6, 1595, (1996).
Content	• Photosensitivity mechanisms • Wave transfer and scattering matrices
Readings	B. E. A. Saleh, M. C. Teich, Fundamentals of Photonics, Wiley, 2019. Chapter 7
Assignment	1st INTERACTIVE GROUP ACTIVITY – ELECTROMAGNETIC PROPAGATION IN DIELECTRICS Application of the description of refraction in dielectrics –Task assignment from industrial fiber optics area

Session 3	STRUCTURAL DISORDER EFFECTS IN THE INTRINSIC ABSORPTION SPECTRUM OF AMORPHOUS DIELECTRICS
Content	• Amorphous dielectrics & description of disorder – Zachariasen criteria • Measuring disorder • Phonon spectrum of topologically disordered amorphous oxides
Readings	N. E. Cusack, The Physics of Structurally Disordered Matter: An Introduction, CRC Press, 1987. F. L. Galeener, Band limits and the vibrational spectra of tetrahedral glasses, Phys. Rev. B 19, 4292 (1979). F. L. Galeener, Planar rings in glasses, Sol. St. Commun. 44, 1037 (1982). A. Pasquarello, R. Car, Identification of Raman Defect Lines as Signatures of Ring Structures in Vitreous Silica, Phys. Rev. Lett. 80, 5145 (1998).
Content	• Disorder and energy gap • Urbach energy and static and dynamic contribution to the absorption edge
Readings	K. Saito and A. J. Ikushima, Absorption edge in silica glass, Phys. Rev. B 62, 8584 (2000). G. D. Cody, T. Tiedje, B. Abeles, B. Brooks, and Y. Goldstein, Disorder and the Qptical-Absorption Edge of Hydrogenated Amorphous Silicon, Phys. Rev. Lett. 47, 1480 (1981). D. Weaire and M. F. Thorpe, Electronic Properties of an Amorphous Solid. I.A Simple Tight-Binding Theory, Phys. Rev. B 4, 2508 (1971).
Assignment	2nd INTERACTIVE GROUP ACTIVITY – AMORPHOUS STRUCTURE AND RELATED OPTICAL PROPERTIES Applications – quantitative analysis of a practical situation – Task assignment for process optimization

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Session 4	SHORT ORDER COORDINATION AND NANOSTRUCTURES – ROLE ON EXTRINSIC OPTICAL PROPERTIES OF DOPED DIELECTRICS – A TOOL FOR CRITICAL ELEMENT SUBSTITUTION STRATEGIES
Content	• Transitions at localized states – homogeneous and inhomogeneous contributions • Electron-phonon coupling – Spectral broadening and Huang-Rhys factor
Readings	L. Skuja, Optical properties of defects in silica, in Defects in SiO2 and related dielectrics, ed. G. Pacchioni, Kluver Acad Pub., 2000. (Sections 1, 2.1,2.2)
Content	• Crystal field effects & Tanabe – Sugano diagrams • Applications of T–S diagrams & Judd-Ofelt theory • Glass vs. Crystal environments and the role of nanostructured dielectrics • Rare Earth ions vs. Transition Metal ions as light-emitting species – substitution & sustainability criteria
Readings	J. Garcia Sole, L. E. Bausa, D. Jaque, An Introduction to the Optical Spectroscopy of Inorganic Solids, Wiley, 2005. R. Rolli, M. Montagna, S. Chaussedent, A. Monteil, V.K. Tikhomirov, M. Ferrari, Erbium-doped tellurite glasses with high quantum efficiency and broadband stimulated emission cross section at 1.5 μm, Opt. Mater. 21, 743 (2003). D. Peck, P. Kandachar, E. Tempelman, Critical materials from a product design perspective, Materials and Design 65, 147 (2015).
Content	• Introductions to optical nonlinearity in amorphous dielectrics • Anharmonic effects, nonlinear refractive index and related mechanisms
Readings	K. S. Potter, J. H. Simmons, Optical Materials, Elsevier Science Publishing Co Inc, 2021. Chapter 7
Assignment	3rd INTERACTIVE GROUP ACTIVITY – MATRIX EFFECTS ON ACTIVE IONS Application of the description of CF effects and nonlinearity – Task assignment on optical device design

Session 5	FINAL EXAM
Dates	JUN 2021, JUL 2021 1st week, JUL 2021 3rd week, SEP 2021, OCT 2021
Content	Oral presentation (interview with extemporaneous written presentation of quantitative analysis, equations, graphs, and schematic drawing and modelling. Duration: about 45 min)

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