EE 383V Quantum Electro-Optics (Fall 2024)

Date/Time/Location: MW / 10:30-11:45 AM / ECJ 1.306

Instructor: Dan Wasserman
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Office Hours:
In-Person, Wednesday 12:00-1:00 PM, EER 3.874
Zoom, Thursday 12:30-1:30PM, https://utexas.zoom.us/j/99631375009
By appointment (Usually Zoom)
Teaching Assistant: Nope

Description: The field of Quantum Electro-Optics (or Nanophotonics) encompasses the set of devices, structures, and materials whose electronic and optical properties cannot be understood using the bulk properties of the constituent materials, but instead depend strongly on both size and geometry. Nanophotonics is an emerging contemporary area of research with a wide range of new applications. Understanding the optical properties of nanometer scale structures of semiconductors, metals, and composites will be crucial for future optoelectronic devices and technology designed to couple with, complement, or possibly even replace, present and future nanoelectronic devices. Separated from any electronic components, nano-scale or subwavelength photonic structures offer new possibilities for sensing, imaging, waveguiding, and many other applications. This course will examine the quantum mechanical interaction between light and semiconductors, metals, and composites; including cavity electrodynamics, polarition cavity condensation, sub-wavelength structures, metamaterials, plasmonics, and applications of the above. Presentations by students are included to develop oral communication skills as well as to incorporate leading-edge research into the course.

Prerequisites: Some exposure to quantum mechanics, semiconductor physics and devices.

Text: Class notes and journal papers

Supplementary:
The Physics of Low-Dimensional Semiconductors, Davies (Cambridge 1998)
The Physics of Photonics Devices, Chuang
Optoelectronics, Rosencher
Fundamentals of Photonics, Saleh and Teich
The Physics of Semiconductors, M. Grundmann (Springer 2006)
Semiconductor Optics, C. Klingshirn (Springer, 2005)
Introduction to Nanophotonics, S. V. Gaponenko (Cambridge 2010)
Optical Processes in Semiconductors, J. Pankove (Dover 1971)
"Physics of Light and Optics" http://optics.byu.edu/textbook.aspx

Grading:

Homework/Attend.	30%/5%	Due ~1 week after assigned
Midterm Exam	35%	In class
Final Project	30%	Presentation & questions

Presentation: Each student will give an in-class presentation focused on a cutting-edge research topic in quantum electro-optics or, alternatively, a numerical program (developed by the student) used for advanced simulation or calculation of a quantum electro-optical phenomenon. Presentations will be 15 minutes long, including 2-3 minutes for questions following the presentation. Presentations will be graded on technical content, oral communication and visual presentation skills, critical thinking, as well as the presenter's ability to answer questions and discuss the presentation topic and its place in the larger context of the field. It is expected that the presentation (or program) will focus *critically* on a sub-field **outside** of the students' current field of research.

Course Administration

Lectures: Lecture will consist of ppt slides as well as whiteboard/ppt annotations made during the lecture. The basic ppt slides will be posted online on Canvas, but for detailed notes or annotations to the slides, students are expected to attend lecture. Though there will not be an attendance roll call, in a small class such as this participation and attendance throughout the semester will be noted. Attendance will account for 5% of the final grade. If a student misses a lecture for any reason, they will be expected to use the on-line notes to bring themselves up to speed. They may also ask classmates to share notes taken in lecture.
The classroom will be enabled with automatic recording technology. This means that lectures will be recorded and automatically posted to Canvas. This will all occur automatically and there is no guarantee that it will work for every lecture. The best way to ensure you are able to view the lectures is to attend in person.

Homework: Homework will be turned in before class on the day that they are due. In response to previous classes' feedback, I have tried to reduce the total number of HW assignments, giving students more time for each assignment. In general, the HW will cover topics covered in the lectures up to and including the Wednesday lecture before the Monday (or Wednesday) of the HW due date. I have Office Hours on Wednesday (in person) and Thursday (Zoom) to provide any help you might need. All homework assignments will be posted to Canvas and their due dates listed on Canvas. No late homework will be accepted. In extreme circumstances, with a letter from Health Services and/or the appropriate administrative official, a homework can be dropped, but only with course instructor approval.

Homework will primarily be a mix of analytical, conceptual, and numerical problems. Students may work in groups to understand the homework problems and to work out approaches to solving them. However, the homework turned in should represent the individual student's ***own*** work, and cannot be copied from another student. Copied/reproduced homework constitutes a violation of the honor code, and will be treated as such.

Analytical Problems: Solutions **must** be legible, and must indicate the approach taken to solve the problem, as well as each step used in the approach. It is the students' responsibility to make clear to the grader how the problem was solved and what the solution to the problem is. Illegible, or poorly annotated/described solutions will receive no credit. For clearly presented, well thought-out solutions, partial credit will be granted even if the solution is not correct.

Conceptual Problems: Conceptual problems will ask for the student to explain in words and/or equations, a physical phenomenon or concept from the course. Answers are expected to be in clear and concise English, and free from grammatical and typographical errors. Students are expected to use their own words, but are free to cite from the literature, as long as all references are clearly noted. Students may also be asked to respond to questions regarding state-of-the-art concepts or research, which will require use of the literature.

Numerical problems: Numerical problems are to be performed in Matlab. You should have free access to Matlab through the University. For those of you not familiar with Matlab, do not despair! Initial numerical problems will be mathematically and conceptually simply and will give you a chance to understand the basic operation and functioning of the software. Later numerical problems will be more complex, both conceptually and mathematically. All numerical homework programs (*.m files) will be turned in electronically on Canvas. Outputs (plots, graphs, tables, etc.) should be clearly labeled and turned with the written HW. A basic example Matlab program is available on the course Canvas website. This program calculates the normal incidence reflection from a dielectric surface as a function of wavelength and plots the results. Your program files should be named using the problem name and your initials (i.e. "DW_Reflection.m"). The first two lines of the script should have the HW, problem name, your full name, your UT EID, and a brief description of the program, as shown in the example script. All numerical homework problems should be clearly and concisely annotated. The grader should be able to clearly see the program inputs (and should be able to change these) and should be able to press the execute button and see the program outputs.

The analytical and conceptual problems will be handed in as hard-copies, with outputs from the numerical problems, clearly labelled, attached to the conceptual/analytical solutions. The code associated with the numerical components will uploaded to Canvas.

Exams: There will be one midterm exam for this course. There used to be two midterm exams, but previous feedback indicating that i) the course workload was high and ii) that homework seemed to be the most valuable part of the class led me to try removing an exam. The midterm exam will be given at approximately the mid-point of the semester, after we have covered the foundational material necessary for understanding Nanophotonics. The exam will be in class, and will cover all of the course material up to the date of the exam. Make-up exams will not be given.

Course Learning Outcomes:

This is mandated by our State Legislature. Interestingly, there are exactly 0 members of our state legislature that understand quantum mechanics, optics, quantum optics, semiconductor band structure, or pretty much any other topic we will cover. I would be willing to place a rather large bet that the percentage of State Legislators that can perform a simple integral is in the single digits. Nevertheless, students should come away from this course with:

- A conceptual and quantitative understanding of light, and the various different ways we can describe and analyze optical signals and modes.
- A conceptual and quantitative understanding of matter, specifically semiconductors, metals, dielectrics, and 2D materials. Understanding of band structure, distribution statistics, density of states, and charge transport.
- Conceptual and quantitative understanding of light-matter interaction, from simple classical 'toy' models all the way to second quantization.
- Current cutting-edge topics in Nanophotonics and Quantum Electro-Optics
- The ability to set up and run simple numerical approaches to understand and simulate fundamental topics in Quantum electro-Optics.

Course Topical Outline.

A full course calendar will be available on the Canvas website.

Foundations

I. Light (Lectures 1-3)
  a. Ray Optics
  b. Wave Optics
  c. Electromagnetics, Maxwell’s Equations
  d. Photon Optics

II. Matter (Lecture 4)
  a. Basic description of atoms and crystals, free and bound electrons
  b. Semiconductors, metals, and insulators: band structure
    i. Kronig-Penney Model
    ii. Band diagrams
    iii. Effective mass
  c. Density of states and distribution functions, doping.
  d. Quantum confinement

III. Phonons (Lecture 5)
  a. Classical oscillator
  b. 1-atom chain
  c. diatomic atom chain
  d. Quantum harmonic oscillator
  e. Phonon Statistics

IV. Light-Matter Interaction (Lecture 6-12)
  a. Bulk Optical Properties of Matter
    i. Toy models of refractive index/optical permittivity
    ii. Reflection/refraction
    iii. Kramers-Kronig relations
  b. Optical transitions
    i. Einstein Coefficients
    ii. Classical Picture of Absorption
    iii. Optical transitions in real materials
    iv. Optical transitions in semiconductors – semiclassical
    v. Optical transitions in semiconductors – dipole moments
    vi. Rabi Oscillations
    vii. Second quantization and spontaneous emission
  c. Polaritons
  d. Non-linear Effects
    i. Raman scattering (quantum/classical)
    ii. SHG, SFG, DFG, 2PA

V. Optical and Electronic Confinement (Lectures 13-17)
  a. Quantum Confinement
  b. Optical Transitions in Quantum Confined Structures
  c. Optical Confinement
  d. Combining Quantum and Optical Confinement (lasers)

Exam I (In Class)

VI. Optical scattering (Lecture 17)

  a. Thomson, Rayleigh, & Mie Scattering
  b. Bragg-mirrors
  c. Photonic Crystals
  d. Photonic crystal defects

VII. Sub-wavelength Optics (Lecture 18)
  a. Gratings (reflection and diffraction)
  b. The diffraction limit
  c. Beating the diffraction limit

VIII. Metallic Optics (Lectures 19-20)
  a. Perfect electrical conductor waveguides
  b. Noble metal optics
  c. Propagating Surface Plasmons
    i. Plasmonic waveguides
    ii. Nano-apertures, aperture arrays
  d. Localized surface plasmons
    i. nano- spheres, -rods, -shells
    ii. Surface enhanced Raman scattering

IX. Metamaterials & Metasurfaces (Lecture 21)
  a. Negative refraction and negative index
  b. Optical transformations

X. 2D Materials (Lecture 23)
  a. Band structure
  b. Optical properties
  c. 2D Plasmonics
  d. 2D Nanophotonics

XI. Nanoscale light matter interaction (Lecture 24)
  a. Purcell Effect
  b. Fano Effect
  c. Nano-emitters and detectors
  d. Nano-scale energy transfer

XII. Special Topics (Time Permitting)
  a. Topological Photonics
  b. Time Crystals
  c. Floquet Engineering

XIII. In-Class presentations