Syllabus: Optoelectronics and Quantum Optics

Jeffrey Yepez

University of Hawai'i Maui College
Science, Technology, Engineering and Mathematics Department
310 Ka'ahumanu Ave, Kahului, HI 96732-1617
yepez@hawaii.edu

(Dated: January 8, 2018)

I. COURSE DESCRIPTION

This is a 3 credit semester long course on optoelectronics for undergraduate senior-year students in the engineering and technology program.

A. Overview

The subject of optoelectronics and semiconductor device physics has a long tradition of combining the disciplines of electrical engineering and applied optics. Today, with the advent of the quantum theory of light and matter as well as related numerical methods in quantum simulation, we have the opportunity to understand the basic operations of optoelectronic devices as a direct application of quantum theory, in particular as an application of the theory of quantum optics. Therefore, the subject material presented in this course is based on the application of the theory of quantum optics to study light generation in semiconductor-based optoelectronic devices. In this course, the student will gain an understanding of the behavior of light-emitting semiconductor processes by modeling basic quantum processes involving the interaction of electrons, electron holes and photons.

Furthermore, in this course, students study light generation and detection in optoelectronic devices such as photovoltaic and photoconductive detectors and phototransistors. The students are expected to model, characterize and test optoelectronic devices such as: light emitting diode (LED), laser diode, photodiode, phototransistor, photoresistor, photomultipler, avalanche photodiode, single-photo avalanche diode, PIN diode, photodiode array, and solar cell. The scientific methods practiced in this course includes mathematical modeling, laboratory experiments and project-based activities. This course provides many practical laboratory applications relevant to Hawaii's high-tech industries and scientific communities.

B. Course plan

Students should have facility with simple linear differential equations (e.g. solvable by using the Fourier transform method) as well as the ability to carryout symbolic mathematical calculations and numerical simulations on a computer. Demonstrations in the class will use Mathematica and this symbolic mathematics software application is highly recommended for the students as an aid to accomplishing the assigned weekly problem sets.

Each student will select an optoelectronincs topic of their choosing for a Final Project.

The Final Project will entail:

1. studying a selected optoelectronic device
2. building an electrical circuit to obtain experimental data for the optoelectronic device
3. analyzing the experimental data with tools and methods presented in the class
4. and comparison of analytical and model predictions obtained from quantum simulation with the observed behavior of the selected optoelectronic device.

Each student will summarize his or her optoelectronics device study in the form of a written Technical Report for turn in as the Final Project.

A basic review/refreshers for linear differential equations and numerical simulation is provided at the outset as needed.

The class meets Monday 3:45-6:00pm and Wednesday 3:45-6:00pm (via VTC).

Office Hours: Immediately following class Monday and Wednesday and by appointment

Prerequisites: MATH 219 or 232, PHYS 219, ETRO 305 and 320 with grade C or better. — This prerequisite cannot be waived.

C. Mathematical skill set

Simple linear differential equations and symbolic computation.

II. PROSPECTUS

1. Introduction
   - Introduction to quantum optics and optoelectronics
2. Introduction to quantum mechanics
   - Quantum mechanics, probability amplitudes and probabilities
   - Time evolution of a single quantum particle via quantum simulation
   - Discrete energy levels (e.g. simple harmonic oscillator)
   - Quantum tunneling through a potential barrier
3. Introduction to solid-state physics
   - Solid-state physics and crystal structure
   - Electron and electron hole
   - Voltage and electric potential
   - Electronic band structure and the Fermi level
4. Interaction of light and matter
   - Overview of quantum electrodynamics
   - Interaction between electrons and photons
   - Atom-light interaction processes
   - Maxwell-Lorentz equations
   - Photoelectric effect and quantized light
   - Transition between discrete levels and Rabi oscillations
5. Midterm
   - Midterm exam (compilation of assigned Problem Sets up to middle of the semester)
   - In-class review of the solution set
6. Introduction to semiconductors
   - Photodectors
   - The p-n junction, reverse biased, depletion region
   - Semiconductor laser, linear laser cavity
   - Zener effect (Zener breakdown) and electron avalanche breakdown
7. Introduction to optoelectronic devices
   - LED, laser diode, photodiode, phototransistor, photoresistor
   - Photomultipler, avalanche photodiode, triggered avalanche current of a p-n junction under reverse bias
   - PIN diode
   - Photodiode array and optical linear encoder
   - Solar cells
8. Single photon detection (time permitting)
   - Single-photo avalanche diode
   - Superconducting nanowire single-photon detector
9. Final exam
   - Final exam (May — compilation of completed assigned Problems) and Final Project submitted in Technical Report format

III. PROBLEM SETS

Problem sets are assigned as needed and tailored to the students' progress. Students generally have one week to complete any given assigned problem set.

Selected Problem Sets will be submitted in Technical Report format using scientific typesetting software. Students should be familiar with technical and scientific writing.

IV. COURSE REQUIREMENTS AND EVALUATION

Labs, written exercises, and computer problems: 30%
(e.g. assigned Wednesday and due the following Wednesday)
Midterm examination: 30%
Final examination: 30%
Class participation: 10%

V. METHOD OF INSTRUCTION

- Scientific presentations
- Internet-based video teleconference
- Mathematica demonstrations
- Class discussions
- Weekly office hours following the class end and can be scheduled on a weekly basis by e-mail request

VI. RESOURCES

- Text book:

  Gilbert Grynberg, Alain Aspect and Claude Fabre, "Introduction to Quantum Optics: From the Semi-classical Approach to Quantized Light", Cambridge University Press (2010)

- Additional reference books:

  J. Singh, "Semiconductor Optoelectronics: An Introduction to Material and Devices," McGraw-Hill (1996)

  Edward S. Yang, "Fundamental of Semiconductor Devices," McGraw-Hill (1978)

- Wikipedia provides many helpful overviews, including for the respective lectures presented in the course:

  1. Quantum mechanics
  2. Probability amplitude
  3. Quantum simulator
  4. Quantum harmonic oscillator
  5. Quantum tunnelling
  6. Solid-state physics
  7. Voltage
  8. Electron
  9. Electron hole
  10. Photon
  11. Crystal structure
  12. Electronic band structure

13. Semiconductor
14. Semiconductor device
15. Electric potential
16. Fermi level
17. Mathematical descriptions of the electromagnetic field
18. Quantum electrodynamics
19. Photoelectric effect
20. Carrier generation and recombination
21. Diode modeling
22. Optoelectronics
23. Photodetector
24. P-n junction
25. Depletion region
26. Semiconductor diodes
27. Laser diode
28. Light-emitting diode
29. LED circuit
30. Photodiode
31. Avalanche photodiode
32. Electron avalanche
33. Avalanche breakdown
34. Zener effect
35. Single-photon avalanche diode
36. Optical linear encoder

- Mathematical physics developments will be provided in class tailored to the skill of the students.

VII. DISABILITY STATEMENT

1. If you have a disability and have not voluntarily disclosed the nature of your disability and the support you need, you are invited to contact Lisa Deneen - Disabilities Coordinator at 984-3227 or Telecommunication Device for the Deaf (TDD) 984-3325 or the Text Telephone (TT) replay service at 643-8833.

2. Reasonable accommodations will be provided for students with documented physical, sensory, systemic, cognitive, learning and psychiatric disabilities. If you believe you have a disability requiring accommodations, please notify Lisa Deneen - Disabilities Coordinator at 984-3227 or Telecommunication Device for the Deaf (TDD) 984-3325 or the Text Telephone (TT) replay service at 643-8833. The Disabilities Coordinator will verify your disability and provide the course instructor with recommendations for appropriate accommodations.