EC585 Quantum Engineering and Technology (QET)

Shall I refuse my dinner because I do not fully understand the process of digestion?
No, not if I am satisfied with the result. (O. Heaviside, Electromagnetic Theory, vol. 2, 1899)

This course introduces graduate students to Quantum Engineering and Technology (QET) by providing a comprehensive and rigorous discussion of the basic principles and engineering design concepts of quantum coherent structures and devices for communications, computation, simulation, metrology, and sensing. The course will provide in-depth discussions of design methods, mathematical techniques, and engineering applications for the control of coherent quantum systems, which emphasis on quantum optical ones, that drive the rapidly emerging "quantum supremacy" paradigm for computing and information processing. This course provides a broad yet rigorous foundation of quantum technology that exploits quantum correlations and coherent superposition effects to achieve fundamentally novel optical and electronic functions on photonic and solid-state devices. A distinctive feature of this course is to present the material in strong partnership with "hands-on" computer simulations using open source codes that demonstrate quantum mechanical principles and ideas "in action".

Course Syllabus

1. **General introduction to the course** (2 lectures)
    - 1.1.1. The quantum manifesto
    - 1.1.2. Quantum technology in industry
    - 1.1.3. Quantum engineers
  - 1.2. *Thinking and questioning in quantum mechanics*
    - 1.2.1. The logic of quantum mechanics through selected examples
      - 1.2.1.1. Stern-Gerlach (SG) and double slit experiments
      - 1.2.1.2. Sequential choice experiments
      - 1.2.1.3. Delayed-choice experiments

2. **A toolbox for quantum engineers** (8 lectures)
  - 2.1. *Description of physical systems in quantum mechanics*
    - 2.1.1. Classical versus quantum systems
    - 2.1.2. Dynamical variables and observables
    - 2.1.3. Quantum state description approach: spin systems
  - 2.2. *The algebra of quantum mechanics*
    - 2.2.1. Linear algebra in Dirac notation
    - 2.2.2. Hilbert Space and function spaces
    - 2.2.3. Linear operators and spectral decompositions
    - 2.2.4. Elements of representation theory
    - 2.2.5. Measurements and uncertainty theorems
    - 2.2.6. Postulates of QM and their physical meaning
  - 2.3. *Observables with continuous spectra*
    - 2.3.1. Position and momentum bases
    - 2.3.2. Change of bases and pulse propagation
    - 2.3.3. The quantum harmonic oscillator
    - 2.3.4. Examples in Matlab and QuTip Python

3. Quantum principles in action (4 lectures)

3.1. *Quantum Dynamics*

3.1.1. Time evolution

3.1.2. Spin qubits and Bloch sphere

3.1.3. Spin dynamics and Bloch equations

3.1.4. Mixed states and density matrix evolution

3.1.5. Open systems and Lindblad-form master equation

3.2. *Composite systems*

3.2.1. Bipartite systems and tensor product space

3.2.2. Entangled states and quantum correlations

3.2.3. Measuring sub-systems

3.2.4. Bell's, CHS, and CHSH theorems

3.2.5. Experimental tests of Bell's inequalities

4. Quantum technology (5 lectures)

4.1. *Quantum logic and circuits*

4.1.1. Quantum registers and parallelism

4.1.2. One-qubit and multi-qubit quantum gates

4.1.3. No-cloning theorem

4.1.4. Superdense coding and quantum teleportation

4.1.5. Elements of quantum circuit theory

4.1.6. Examples in Matlab and QuTip Python

4.2. *Intro to quantum algorithms*

4.2.1. The Deutsch and Deutsch-Jozsa algorithms

4.2.2. The quantum Fourier transform

4.2.3. The Shor algorithm

4.2.4. Examples in Circ and QuTip python

4.3. *Quantum communication and cryptography*

4.3.1. Intro to classical crypto: symmetric and public key ciphers

4.3.2. Quantum mechanics of free-photons: polarization states

4.3.3. Quantum Cryptography: Wisner's main idea

4.3.4. Quantum key distribution: BB84 and B92

4.4. *Quantum metrology and sensing*

4.4.1. Interferometry with single photons: path interference

4.4.2. Interaction-free measurements

4.4.3. Quantum metrology and sensing with N-photon states

5. Photons and atoms as quantum information carriers (4 lectures)

5.1. *Quantum oscillations in action*

5.1.1. Anharmonic and coupled quantum oscillators

5.1.2. EM field quantization – canonical quantization

5.1.3. Intro to quantum states of light: coherent states and squeezing

5.1.4. The quantum beam splitter and interferometer

5.2. *Photons and single-photon sources*

5.2.1. Entangled and single-photon sources

5.2.2. Dual-rail qubit representation

5.2.3. Quantum communication with single photons

5.3. *Optical quantum information processing*

5.3.1. Atom-field interaction: the Jaynes-Cummings model

5.3.2. Vacuum Rabi oscillations and coherent atomic control

5.3.3. High-Q optical cavities approaches to photon circuits
5.3.4. Atom and ion traps technology
5.3.5. Circuit models of superconducting quibits
5.3.6. Examples in Matlab and QuTip Python

Topics for final projects

1.1. Photonic quantum networks
1.2. Cavity QED computing systems
1.3. Quantum cryptography
1.4. Superconducting quantum circuits
1.5. Quantum radars
1.6. Linear optical quantum computing (LOQC)
1.7. Quantum sensing and metrology
1.8. Quantum algorithms
1.9. The Jaynes-Bose-Hubbard model of Cavity-QED

Suggested textbook

Notes prepared by the instructor are distributed per class topic.

Background references

- *Quantum Mechanics: The theoretical minimum* by L. Susskind and A Friedman, Basic Books 2014 (attention: strongly advised to read this book independently before the beginning of the course)
- *Modern Quantum Mechanics,* by J. J. Sakurai and Jim Napolitano, Cambridge University Press, 2017
- *Introduction to Optical Quantum Information Processing*, by Pieter Kok and Brendon W. Lovett, Cambridge University Press, 2010
- *Quantum Engineering: Theory and Design of Quantum Coherent Structures*, by A. M. Zagoskin, Cambridge University Press. 2011
- *Quantum computation and information*, by Michael A. Nielsen and Isaak L. Chuang, Cambridge University Press, 2011

Prerequisites: CAS MA 225 (Multivariate Calculus), Linear Algebra, **ENG EK 127/128** (Engineering Computation), **ENG EK 102/CAS MA 142** (Intro linear algebra), **CAS PY 313 / 314** (Waves and Modern Physics). Background knowledge in classical electrodynamics, semiconductors physics, and quantum mechanics. Talk to the instructor before registering if unsure.