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 the mathematical foundation, selected design methods, and in-depth discussions of engineering device implementations of coherent quantum systems, with emphasis on quantum optical ones. The course provides a broad yet rigorous training in quantum mechanics for engineering students interested in understanding both the technical applications and the broader societal impact of quantum principles in technology.

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: a primer*
        - 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
            - 1.2.1.4. What is a measurement, really?

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 (Dirac formalism)*
        - 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. Transition rates and perturbation theory

3. **Quantum principles in action** (4 lectures)
   - 3.1. *Quantum Dynamics*
     - 3.1.1. Time evolution and quantum dynamics
     - 3.1.2. Spin qubits and Bloch sphere dynamics
     - 3.1.3. Quantum beats and qubit Hamiltonians
     - 3.1.4. Spin dynamics and qubit engineering
     - 3.1.5. Mixed states and density matrix evolution
     - 3.1.6. Open systems and Lindblad-form master equation
     - 3.1.7. Engineering device applications (flux and charge qubits)
   - 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, partial trace
     - 3.2.4. Schmidt decomposition
     - 3.2.5. Bell's, CHS, and CHSH theorems
     - 3.2.6. Experimental tests of Bell's inequalities
     - 3.2.7. Elements of measurement theory (Von Neumann chains)

4. **Quantum technology** (5 lectures)
   - 4.1. *Quantum logic and circuits*
     - 4.1.1. Basic quantum gates
     - 4.1.2. Quantum registers and parallelism
     - 4.1.3. One-qubit and multi-qubit quantum gates
     - 4.1.4. No-cloning theorem
     - 4.1.5. Superdense coding and quantum teleportation
     - 4.1.6. Elements of quantum circuit theory
     - 4.1.7. 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. Quantum noise: basic measurements and techniques
     - 4.4.2. Interferometry with single photons: path interference
     - 4.4.3. Interaction-free measurements
     - 4.4.4. Quantum metrology and sensing with N-photon states
     - 4.4.5. Quantum nondemolition measurements

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 – single and multiphoton states
      5.1.3. Intro to quantum states of light: coherent states, squeezing, two-photon states
      5.1.4. Coherence properties, correlation functions, photon correlation measurements
      5.1.5. The quantum beam splitter and interferometer
   5.2. *Photon detection and single-photon sources*
      5.2.1. Introduction to photon counting: theory and measurements
      5.2.2. Entangled and single-photon sources
      5.2.3. Dual-rail qubit representation
      5.2.4. 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 approach to photon circuits
      5.3.4. Atom and ion traps technology
      5.3.5. Circuit models of superconducting quibits

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. Linear optical quantum computing (LOQC)
1.6. Quantum sensing and metrology
1.7. The Jaynes-Bose-Hubbard model of Cavity-QED

Suggested textbook

Introduction to quantum Technologies by A. Osada, R. Yamazaki, A. Noguchi. Springer, 2022
Notes prepared by the instructor are distributed per class topic along with relevant papers.

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

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 elementary quantum mechanics.