# Quantum Circuits

Period: Spring IV

**Prerequisites**: Basic knowledge in quantum mechanics including second quantization and harmonic oscillator. Basic knowledge on condensed-matter physics.

**Course summary:** The physical foundations and implementation of solid-state quantum electronics has attracted broad interest in the context of realization of quantum information processing systems. In this course, we address the physics of superconducting quantum circuits and show how such circuits can be implemented based on superconducting thin films and nanostructures. We discuss the application of superconducting quantum circuits in quantum information processing systems and in quantum simulation.

The following specific topics will be addressed:

- Josephson effect and Josephson junction as a circuit element
- systematic quantization of a network of lumped-element electric components such as capacitors, inductors, and Josephson junctions
- classical description of electromagnetics in one-dimension: voltage and current fields
- quantum mechanics of one-dimensional transmission lines and resonators
- cavity-qubit systems and the Jaynes-Cummings model
- operation of superconducting qubits: reset, quantum logic, and readout.
- implementation of quantum gates in quantum computers

**Learning outcomes**

- Apply the theoretical framework of quantum mechanics in electric circuits and devices, that is, circuit quantum electrodynamics
- Design and model superconducting quantum circuits: from resonators to qubits
- Identity electrical circuits of practical interest that behave quantum mechanically
- Distinguish between linear and non-linear electronic systems and utilize them for the desired functionalities
- Hypothesize on the behavior of quantum systems

**Lectures:** 24 h, exercises: 12 h, exam: 3 h + independent work

**Exercises:** cover the lectures of Mon + Wed; discussed on Friday the same week in the exercise session; due on Wed. (before the lecture) the week after. Exceptions to this scheduling may happen due to legal holidays, holiday breaks, etc.

**Grading system:** 50% exercises, 50% final exam.

**Threshold for passing the course:** 50% of assignments in both exercises and exam.

# Course outline:

1. **Lecture 1:** ***Key concepts from quantum mechanics and solid-state physics***. Hilbert space, qubits and harmonic oscillators. Quantum mechanics in second quantization formulation. Density of states.
2. **Lecture 2:** ***Components***. Resistors, capacitors, inductors, filters, lumped-circuit resonators.
3. **Lecture 3:** ***Transmission lines*.** Physical realization and modeling of transmission lines and waveguides. General models for the propagation of the electromagnetic field.
4. **Lecture 4:** ***Resonators from transmission lines.*** Loaded transmission lines. *Resonators from sections of transmission lines***.** Introduction to simulation of transmission lines and resonators.
5. **Lecture 5:** ***COMSOL demo***: microwave engineering *of* transmission lines.
6. **Lecture 6***:* ***Introduction to superconductivity.*** Phenomenology and London equations. The superconducting order parameter and phase.
7. **Lecture 7:** ***Josephson effect****.* Tunnel barriers and the Josephson effect. Interference and SQUIDs.
8. **Lecture 8:** ***Quantization of electrical networks***. DiVicenzo criteria and how they are related to this course. Basic concepts: Lagrangian, Legendre transform to Hamiltonian. Example 1: harmonic oscillator. Example 2: an-harmonic oscillator. Example 3: harmonic oscillator coupled to qubit.
9. **Lecture 9:** ***Superconducting quantum bits***. Introducing the transmon qubit, the charge qubit, and the flux qubit. Elements of circuit QED: the Rabi model and the Jaynes-Cummings model.
10. **Lecture 10:** ***Single-qubit operations****.* The transmon: initialization, control and readout. T1 and T2 measurements. Randomized benchmarking.
11. **Lecture 11:** ***Architectures for 2-qubit gates*.** Realization of: iSWAP, cPhase, and CNOT. Deep dive: Google's quantum supremacy experiment.
12. **Lecture 12:** ***Quantum computing: algorithms and future challenges****.* Overview of VQE and Grover search, scaling, the SW-HW gap, and error-correction

| **Lectures and topic** | Lecture date | Exercise discussion session due date | TA |
|---|---|---|---|
| Lecture 1: **Key concepts from quantum mechanics and solid-state physics** | 26-02 | Ex 1<br>01-03<br>06-03 | Aashish |
| Lecture 2: **Components** | 28-02 | | |
| Lecture 3: **Transmission lines** | 04-03 | Ex 2<br>8-03<br>13-03 | Aashish |
| Lecture 4: **Resonators from transmission lines** | 6-03 | | |
| Lecture 5: **COMSOL (demo)** | 11-03 | Ex 3<br>15-03<br>20-03 | Aashish |
| Lecture 6: **Introduction to superconductivity** | 13-03 | | |
| Lecture 7: **Josephson effect** | 18-03 | Ex 4<br>22-03<br>27-03 | Aashish |
| Lecture 8: **Quantization of electrical networks** | 20-03 | | |
| Lecture 9: **Superconducting quantum bits** | 25-03 | Ex 5<br>27-03<br>10-04 | Aashish |
| Lecture 10: **Single-qubit operations** | 27-03 | | |
| Lecture 11**: Architectures for 2-qubit gates** | 08-04 | Ex 6<br>12-04<br>17-04 | Aashish |
| Lecture 12: **Quantum computing: algorithms and future challenges** | 10-04 | | |

Exam: 17-04

**Textbooks:**

Juan Jose Garcia-Ripoll, Quantum Information and Quantum Optics with Superconducting Circuits, Cambridge University Press (2022).