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Lasing, Cooling, and Nonequilibrium Photon States in Circuit QED

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Several of the concepts originally introduced in quantum electrodynamics (QED) have been reproduced and extended in recent experiments with superconducting quantum circuits. In these systems a single qubit (or few) is coupled to a microwave resonator. Lasing and cooling of the resonator as well as nonequilibrium photon states, incl. Fock states, have been observed. Apart from the similarities to quantum optics there exist important differences, some of which will be addressed in this talk: (i) Circuit QED provides realizations of "single-atom lasers," with the atom being replaced by a superconducting qubit. The low number of degrees of freedom makes the quantum nature of the field visible. As a result in single atom lasers the lasing transition is smeared. On the other hand, the permanent qubit - resonator coupling allows exploring the specific properties of single-atom lasing. (ii) The coupling between qubit and resonator may be very strong, giving rise to qualitatively new effects. For instance, strong coupling can lead to multiple optimal regimes for lasing and a double peak structure in the resonator output spectrum. In addition higher order correlations gain quantitative importance. (iii) Decoherence and relaxation effects need to be accounted for. The large line-width observed in single-qubit lasers is mainly due to low-frequency noise, which renders the line-shape Gaussian rather than Lorentzian. (iv) Circuit QED offers new ways to drive the qubit, e.g., the qubit may consist of a driven superconducting single-electron transistor, or to engineer resonators with specific anharmonicities. (v) A variety of resonant conditions can be exploited, including the situation where the low Rabi-frequency is in resonance with a slow oscillator.