Generation of Fock states in a superconducting quantum circuit

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Microwaves, despite their name, are particles. However the photon quanta of microwave fields are rather pusillanimous. They carry four to five orders of magnitude less energy than optical photons and are correspondingly vastly more difficult to detect and count. Nevertheless, recent progress in atomic cavity QED [1] and superconducting circuit QED [2] has achieved this. Single-photons-on-demand as well as coherent superpositions of 0 and 1 photons have been generated in a microwave resonator electrical circuit. [3]

A classical signal generator produces a sine wave of constant amplitude, frequency and phase. The quantum equivalent (produced by a laser or a microwave signal generator) is a so-called coherent state. Because the phase is sharply defined, the photon number (which is the conjugate variable), is necessarily ill-defined. The number of photons to be found in a coherent pulse is in fact Poisson distributed. As a result, a coherent pulse which contain $\bar{N}$ photons on average will have a variance in photon number of $\sqrt{\bar{N}}$. These closest cousins to classical waves are of course useful but not terribly exciting. There is great current interest in generating highly non-classical states of the electromagnetic field for purposes of quantum communication and quantum information processing. One interesting and highly non-classical class of states are the Fock states. These are electromagnetic pulses which contain exactly n photons where n is some specified integer. Because they have definite photon number, the phase suffers complete quantum uncertainty. Hence the electric field of such pulses is completely uncertain, a fact which has recently been verified. [3]

Hofheinz et al. have made a tour-de-force advance by deterministically generating photon number Fock states containing up to $N = 6$ photons ($N = 15$ in recent unpublished work) using a superconducting qubit coupled to a resonator.

The resonator supports discrete modes at integer multiples of the fundamental. Because the modes are widely spaced in frequency for short resonators, only one mode is in the experimentally relevant frequency range and the others can be ignored. The relevant mode is a harmonic oscillator with energies $E_n = n\hbar\omega_0$ and we interpret n as the number of photons. A coherent drive applied to this harmonic oscillator can only produce a coherent state, which is a superposition of different photon number eigenstates. In order to achieve 'number squeezing' to produce a Fock state (photon number eigenstate), one must have anharmonicity in the circuit. This anharmonicity is supplied by the Josephson junction which makes the energy levels of the qubit non-uniformly spaced in energy. For sufficiently large anharmonicity the transition frequency that excites the qubit from the ground to first excited state is off resonant for all other transitions, and the qubit can be approximated as a two-level system. Applying a 'π pulse' to put the qubit into its excited state corresponds to the absorption of precisely one photon from the drive field.

Photon number eigenstates in the cavity are generated following a protocol proposed by Liu et al. [4] of repeatedly applying a π-pulse to excite the two-level qubit and then bringing the qubit into degeneracy with the resonator for precisely the right length of time to transfer the energy quantum into the resonator. This time interval is shorter (by a factor of $1/\sqrt{n}$) for each successive transfer and so very precise timing of a complex sequence of control signals is required to carry out the experiment.

Hofheinz et al. count the number of photons by bringing the qubit into degeneracy with the cavity and measuring the rate of Rabi flopping of the energy between the cavity and the qubit. Because of the way harmonic oscillator matrix elements work, this rate scales as $\sqrt{n}$ which allows n to be measured.

References:

1. For a recent entré to the literature from the ENS group, see Delèglise et al., *Nature* **455**, 510 (2008).

2. D.I. Schuster et al., *Nature* **445**, 515 (2007).

3. A.A. Houck, et al., *Nature* **449**, 328 (2007).

4. Y.-X. Liu, L.F. Wei and F. Nori, *Europhys. Lett.* **67**, 941 (2004).