Single artificial-atom lasing

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Recommended and Commentary by Steven M. Girvin, Yale University

The current rapid pace in the experimental development of quantum optics of electrical circuits is quite remarkable. Microwave generators play the role of drive lasers and superconducting circuit elements play the role of artificial atoms and resonant cavities. The relatively large size of the artificial atoms and the small size of the cavities that can be engineered means that extremely strong atom-photon coupling can be achieved relatively easily.

Astafiev et al. have created an all-electrical single-atom laser using a Cooper pair box (CPB) as the artificial atom. The charging energy and bias voltages of the CPB are such that the CPB is operating in a regime where effectively there are three quantum levels and the system is continuously pumped using an electrical current. The authors also present possible evidence for two photon lasing [1], something difficult to achieve in ordinary atomic systems.

The Josephson junction is a circuit element which is simultaneously nonlinear and non-dissipative. It is being used in a variety of different implementations to create qubits (artificial two-level atoms) for use in quantum computation. Current is carried through a Josephson junction by the coherent tunneling of Cooper pairs from one side of the junction to the other. Because the Cooper pairs move from one condensate to another, energy is conserved and dc current can flow only at zero bias voltage. In a normal metal junction, there is a continuum of energy levels available to the electrons and energy conservation in the presence of a finite voltage bias is not a restriction. In contrast, for a Josephson junction, Cooper pairs tunneling across a finite voltage drop V cannot conserve energy and must tunnel back to the original electrode. This leads to the AC Josephson effect in which the current oscillates at a frequency given by $\hbar\omega = (2e)V$ and little or no dc current flows.

If there were a way for the Cooper pair to shed its excess energy of $(2e)V$ it could fall down into the condensate in the second electrode and a dc current could flow. One mechanism for such inelastic tunneling is for the Cooper pair to shake off a photon excitation into the electromagnetic environment surrounding the junction. Because we are in the microwave regime these photons do not fly off into free space very efficiently but instead tend to travel along the wires of the circuit which act as transmission lines. If the voltage bias is such that the energy released in the Cooper pair tunneling process happens to match a resonance frequency of the circuit, this inelastic process is enhanced and there is a peak in the dc current at that particular voltage bias. This effect has been seen by the Rimberg group [2] some time ago in an experiment closely related to that of Astafiev et al. . Many years earlier, the Saclay group [3] used a mechanical sliding short on a transmission line to adjust the resonance frequency of the environment seen by a Josephson junction. Using this they were able to modify the macroscopic quantum tunneling rate out of the initial state of the junction circuit.

A superconducting single electron transistor (SSET) consists of a small metallic grain (island) connected to source and drain leads via Josephson junctions. If the island has an appropriately engineered charging energy, then there are a number of different processes that can lead to resonant Cooper pair tunneling. Depending on the precise values of the source-drain voltage and the gate voltage, Cooper pairs will need to emit energy into the environment or absorb energy from it if DC current is to flow. The latter was predicted to lead to cooling of the environment [4]. This back action effect was recently observed by the Schwab group who used the SSET readout of a nano-mechanical cantilever to provide cold damping of the cantilever [5].

Astafiev et al. have used a SSET coupled to a microwave resonator to produce a single atom laser. The details of the process are quite complex and involve the breaking of Cooper pairs as well as coherent Cooper pair tunneling. Greatly over simplifying, we can say that voltage bias on the SSET gives the Cooper pairs excess energy when they tunnel which is released by adding photons to the cavity. Because the SSET charging energy is significant, the pairs tunnel through sequentially in a correlated manner. Theoretically [1,6,7] this process is much more quantum mechanical than the essentially classical process of lasing generated by coupling the AC Josephson oscillations of many (large, low charging energy) junctions to a resonator which was achieved by the Maryland group some time ago [8], (though the complete theory in the parameter regime relevant to the experiment of Astafiev et al. has yet to be worked out). In this quantum limit it should be possible to see the more complex photon statistics seen in single atom cavity QED lasers [9]. All we need is to develop a good photomultiplier for microwave photons...

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