Controllable States of Superconducting Qubit Ensembles

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Collective states of qubits talking to each other through a quantum field is one of the most interesting and most investigated subjects in quantum optics and information processing. A study of collective effects in two-level atomic systems was initiated by Dicke in 1954 [1] who introduced super- and subradiance effects in ensembles of qubits. Unfortunately, the Dicke model is difficult to realize precisely and controllable in natural systems, such as neutral atoms or ions. At the same time, superconducting microwave circuits have demonstrated strong coupling effects for low excitations and a small number of qubits [2]. Moreover, superconducting qubits can be tuned in frequency, designed in various geometries, and positioned with nanometer accuracy which is much smaller than microwave wavelength. Hence, the circuit QED approach holds much promise for intermediate size multi-qubit systems that realize the Dicke model.

Cavity QED

Periodically Pulsed Quantum Light is a result of the constructive rephrasing in subensembles of spins in the frequency comb [3].

Let us consider an inhomogeneous ensemble of N spins $(\omega_k, \Delta\omega, \gamma_k, \Omega^2 = \sum_k g_k^2)$ coupled to the cavity (ω_c, κ). The cavity is driven by a coherent pulse $(\omega_p, \eta, t' = \frac{2\pi}{5\Delta\omega})$.

The Hamiltonian of the driven system is:

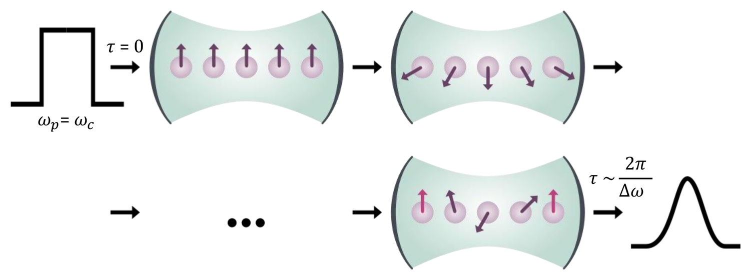
$$\hat{H}_{TC} = \omega_c \hat{a}^\dagger \hat{a} + \frac{1}{2}\sum_{k=1}^{N} \omega_k \sigma_k^z +$$

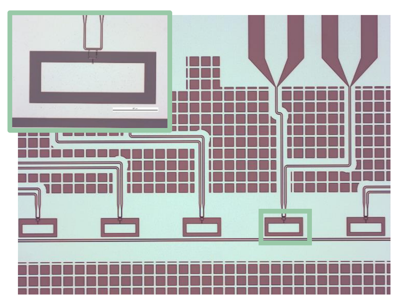
$$+ i\sum_{k=1}^{N} g_k(\sigma_k^- \hat{a}^\dagger + \sigma_k^+ \hat{a}) + i(\eta(t)\hat{a}^\dagger e^{-i\omega_p t} - \eta^*(t)\hat{a} e^{i\omega_p t}).$$

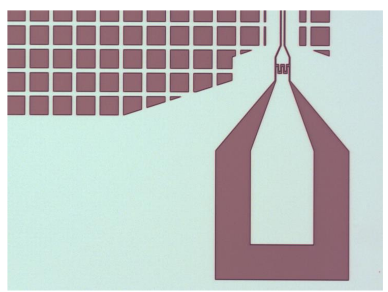
The dynamics of the system is described by a Lindblad master equation:

$$\dot{\rho} = -i[\hat{H}_{TC}, \rho] + \kappa \mathcal{L}_{\hat{a}}[\rho] + \sum_k \gamma_k \mathcal{L}_{\sigma_k}[\rho].$$

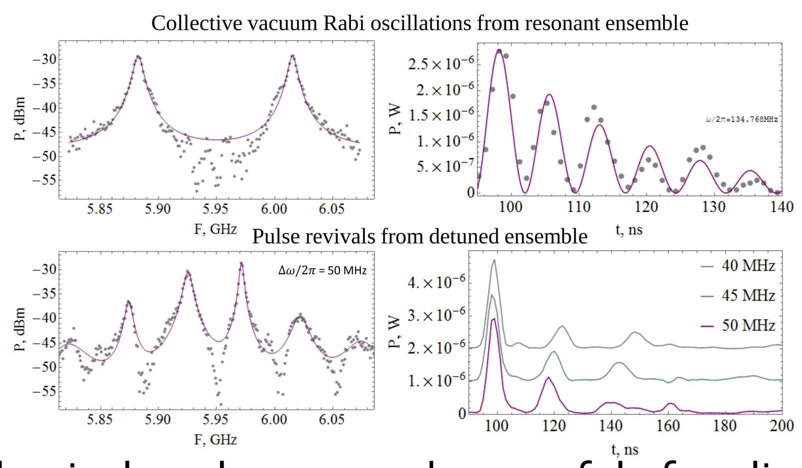
A short microwave pulse at the bare resonator frequency excites all qubits in the ensemble and induces a rotation over the Bloch sphere with the speed proportional to their detuning.







In contrast with one qubit in the cavity where an excitation from the pulse results in vacuum Rabi oscillations, we should observe a pulse train of a nonclassical light from collective interactions in the spin ensemble.



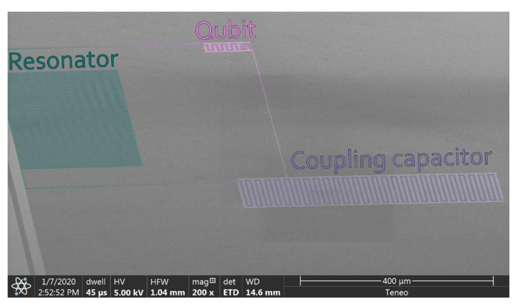
Periodic nonclassical pulses can be useful for linear optical quantum computing [4], single-photon cryptography [5], and temporal synchronization in quantum communication[6] and quantum memory protocols [7].

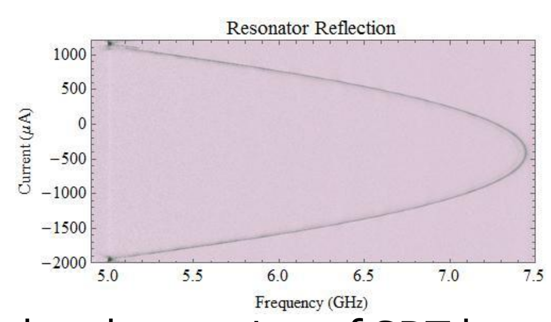
Superradiant Phase Transition (SPT) is one of the most intriguing and debatable prediction based on the Dicke model of superradiance [8,9]. It occurs when the strength of the interaction between the atoms and the field in a cavity is greater than the energy of the non-interacting part of the system. The collective Lamb shift, relating to the system of atoms interacting with the vacuum fluctuations, would become comparable to the energies of atoms alone, and the vacuum fluctuations would cause the spontaneous self-excitation of matter.

However, the Hamiltonian of the ultra-strongly $(g \sim \omega)$ coupled system should include the $\mathbf{A}^2$ term of the field as well as direct dipole-dipole coupling between qubits [10]:

$$\hat{H}_{EDM} = \omega_c \hat{a}^\dagger \hat{a} + \omega \hat{S}_z + g(\hat{a}^\dagger + \hat{a})\hat{S}_x + \frac{g}{\omega}(1+\varepsilon)\hat{S}_x^2.$$

For the experimental realization of SPT, the first task is to achieve an ultra-strong coupling between a single qubit and the resonator. In the case of a charge qubit, it can be done by increasing the coupling capacitor. Based on the observed resonator dispersive shift, we estimated $g \sim 0.2\ \omega$.



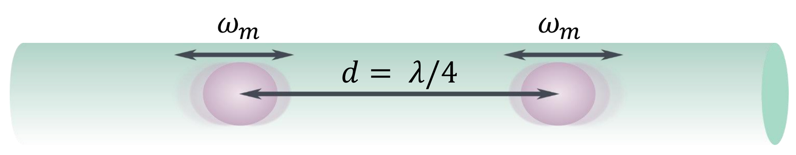


Ultra-strong coupling in not only crucial for the observation of SPT but can also be used to study new photon-blockade regimes [11] and to generate multi-qubit entanglement [12].

Waveguide QED

Tunable Directional Scattering originates from the vibration-induced effective multipole conversion similar to the Kerker effect [13, 14].

Two qubits coupled to a transmission line are tuned in resonance with each other such that the distance between them corresponds to a quarter wavelength. Then, the transition frequency is modulated with ω_m.



The Hamiltonian of the pair of qubits coupled to a waveguide is:

$$\hat{H} = -i\int a_R^\dagger(x)\partial_x a_R(x)dx + i\int a_L^\dagger(x)\partial_x a_L(x)dx +$$

$$+\sqrt{\gamma}[S_1^+ a_R + S_1^+ a_L + S_2^+ a_R e^{i\omega_0 d} + S_2^+ a_L e^{-i\omega_0 d} + h.c.] +$$

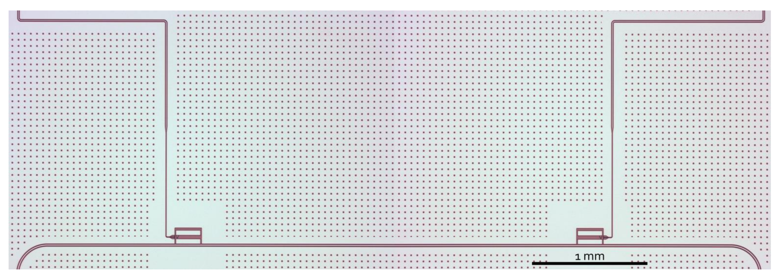
$$+ (\omega_0 + A\cos(\Omega t))S_1^z + (\omega_0 + A\cos(\Omega t + \beta))S_2^z.$$

Interference between the qubits enables directional forward or backward scattering of Stokes and anti-Stokes components depending on the relative phase β between the local driving tones.

$$t_{St} \sim (1 + e^{i\beta})e^{i\omega_0 d},$$

$$r_{St} \sim 1 + e^{i\beta}e^{2i\omega_0 d}.$$

We realize a periodical modulation of the qubit frequency with local flux-lines coupled to the SQUIDs of transmon qubits.

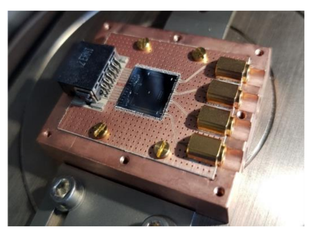


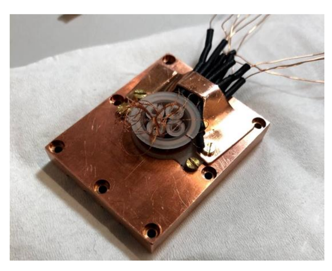
Tunable directional scattering is important for routing of light [15, 16] and the design of topologically protected states [17].

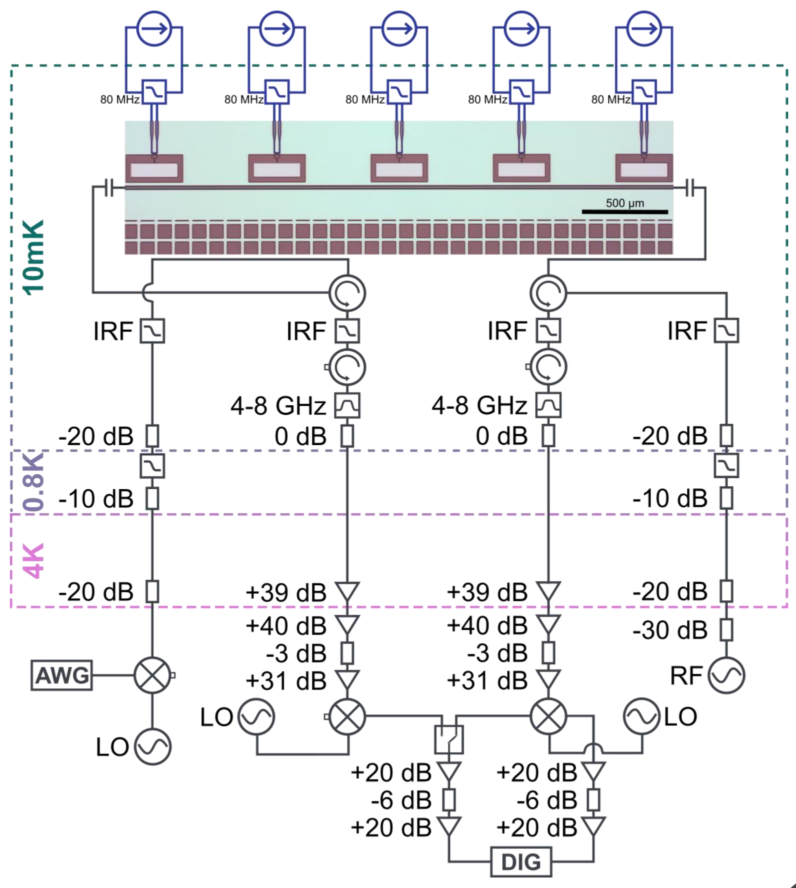
Measurement setup

Experimental studies of superconducting qubits require a mK temperature environment and low electro-magnetic noise level. Hence, our samples are cooled to 10 mK in a cryogenic dilution refrigerator and shielded by two magnetic shields and a radiation shield.

Control over the qubit frequency is achieved by local on-chip bias-lines and off-ship magnetic coils connected to low noise current sources.







References

[1] R. H. Dicke, Phys. Rev., 93(1):99 (1954).
[2] M.H. Devoret, S. Girvin, and R. Schoelkopf, Annalen der Physik,16(10-11):767–779 (2007).
[3] H. S. Dhar, M. Zens, D. O. Krimer, and S. Rotter, Phys. Rev. Lett., 121, 133601 (2018).
[4] E. Knill, R. Laflamme, and G. J. Milburn, Nature409, 46 (2001).
[5] A. Beveratos, R. Brouri, T. Gacoin, A. Villing, J. P. Poizat, and P. Grangier. Phys. Rev. Lett., 89, 187901 (2002).
[6] D. Bouwmeester, J. W. Pan, K. Mattle, M. Eibl, H. Weinfurter, and A. Zeilinger, Nature, 390, 575579 (1997).
[7] M. Afzelius, C. Simon, H. de Riedmatten, and N. Gisin, Phys. Rev. A, 79 , 052329 (2009).
[8] K. Hepp and E. H. Lieb, Annals of Physics, 76(2):360–404 (1973).
[9] Y. K. Wang and F.T. Hioe, Phys. Rev. A, 7(3):831 (1973).
[10] D. De Bernardis, T. Jaako, and P. Rabl, Phys. Rev. A, 97(4):043820 (2018).
[11] A. Ridolfo, M. Leib, S. Savasta, and M.J. Hartmann, Phys. Rev. Let., 109(19), 193602, (2012).
[12] X. Liu, Q. Liao, G. Fang, and S. Liu, Scientific Reports, 9(1), 1-8, (2019).
[13] M. Kerker, D.-S. Wang, and C. L. Giles, J. Opt. Soc. Am. 73, 765 (1983).
[14] A. V. Poshakinskiy, A. N. Poddubny, Phys. Rev. X 9, 011008 (2019)
[15] M. I. Mishchenko, L. D. Travis, and A. A. Lacis, Cambridge University Press, UK, (2002).
[16] P. Lodahl, S. Mahmoodian, S. Stobbe, A. Rauschenbeutel, P. Schneeweiss, J. Volz, H. Pichler, and P. Zoller, Nature 541, 473 (2017).
[17] L. Lu, J. D. Joannopoulos, and M. Soljacic, Nat. Phys. 12, 626 (2016).

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