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QUANTUM INFORMATICS

Observation of a Collective Mode of an Array of Transmon Qubits

K. V. Shulga[a, b, e, f*], P. Yang[c], G. P. Fedorov[e, f], M. V. Fistul[a, d, e], M. Weides[c], and A. V. Ustinov[a, c, e]

[a] *National Research Technological University MISiS, Moscow, 119049 Russia*
[b] *Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka, Moscow region, 142432 Russia*
[c] *Physikalisches Institut, Karlsruhe Institute of Technology, D-76131, Karlsruhe, Germany*
[d] *Theoretische Physik III, Ruhr-Universität Bochum, D-44801 Bochum, Germany*
[e] *Russian Quantum Center, Skolkovo, Moscow region, 143025 Russia*
[f] *Moscow Institute of Physics and Technology (State University), Dolgoprudnyi, Moscow region, 141700 Russia*
**e-mail: kirill_shulga@protonmail.ch*

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Arrays of transmon qubits coupled to a $\lambda/2$ superconducting coplanar waveguide resonator have been studied by microwave spectroscopy. The emergence of a collective mode has been discovered for a cluster of $N > 5$ qubits, whose coupling constant to the electromagnetic field in the resonator is $\sqrt{N}$ times greater compared to a single qubit. In addition, the emergence of collective multiphoton transitions exciting higher levels of a qubit cluster has been demonstrated and the interaction of an individual qubit with such a cluster has been investigated.

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Quantum metamaterials are media consisting of a large number of “atoms,” i.e., artificial two-level systems with controllable properties. Such systems can support collective modes that appear owing to coherent oscillations of the “atoms.” The atoms of ordinary matter are quantum systems with discrete levels, transitions between which occur under external resonance excitation. Such two-level systems in a quantum metamaterial can be artificially prepared superconducting qubits [1] united into a single large array. Qubit arrays have an important specific advantage over individual qubits: their expected coupling $\tilde{g}$ to the electromagnetic field is stronger and proportional to the square root of the number N of qubits.

In this work, we describe the prepared and studied system consisting of so-called transmon qubits [2] situated near a $\lambda/2$ coplanar resonator and coupled to the resonator by the electric field. Investigation of this kind was previously carried out with the use of quantum metamaterials based on flux qubits with a magnetic coupling [3]. In this work, we will show that the use of transmons in the metamaterial allowed exciting collective multiphoton transitions to higher energy levels of the qubits owing to a weaker anharmonicity of the transmon spectrum. In addition, a larger area of Josephson junctions (compared to flux qubits) provided a smaller scatter of the qubit parameters within the array and, consequently, a more pronounced coherent behavior.

The sample under investigation included two nominally identical arrays of 20 transmons and each array was coupled to a separate resonator. The resonators were capacitively coupled to a transmission line (Fig. 1), through which a low-power microwave signal was supplied. The intrinsic Q factors of the resonators determined by measuring the resonance drops in the spectrum S_{21} of the microwave power transmitted through the sample were quite low ($Q \simeq 5000$) compared to similar resonators without qubits.

The Josephson junctions in the transmons were fabricated by shadow evaporation technique deposition of thin-film aluminum structures with AlO_x tunneling barriers. All 20 transmon qubits had identical geometry including a DC-SQUID used as a Josephson junction with a tunable critical current shunted by an additional planar capacitor. The magnetic field applied to the SQUID ring changes the energy splitting between the qubit levels. The qubits were arranged on a silicon substrate at an equal distance from the central line of a coplanar aluminum resonator in the region of the maximum electric field. The Josephson and charging energies of a single transmon were, respectively, $E_J = 19.86h$ GHz and $E_C = 0.29h$ GHz and, consequently $E_J/E_C = 68.4$ (here, h is the Planck constant). The designed transition frequencies between the qubit levels were $f_{01} = 6.503$ GHz and $f_{12} = 6.213$ GHz.

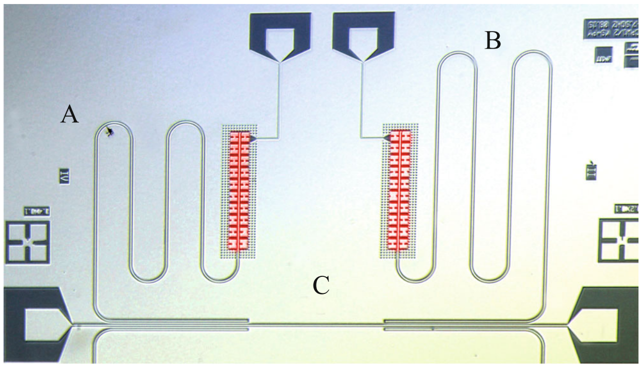

Fig. 1. (Color online) Optical photograph of the sample with two $\lambda/2$ resonators A and B coupled to a transmission line C. Each resonator has 20 transmon qubits (marked in red) coupled to the resonator at one of its ends.

The measurements were carried out in a dilution refrigerator cryostat at a temperature of about 20 mK. In the experiment, the frequency dependence of the transmission coefficient $|S_{21}|(f)$ of microwaves through the coplanar transmission line coupled to the system under investigation was measured by a vector network analyzer. This dependence exhibits resonance minima at frequencies associated with resonance excitation of quantum oscillations in the system. To apply a uniform static magnetic field perpendicular to the substrate to the qubits, a superconducting inductance coil was wound around the sample holder. To avoid interference between the qubit signal and the parasitic electromagnetic modes, whose frequencies are determined by the environment of the experimental chip, we used a special sample holder suppressing this effect [4] by reducing the internal volume of the resonator above the sample and, accordingly, increasing all parasitic frequencies above the frequencies measured in the qubits.

The presence of a large number of distinct qubits in the system provides a plenty of anticrossings of the quantum levels of the qubits and resonator. In our case, the possibility of the emergence of a multitude of anticrossings is caused by the imperfection of the technological process, by which two absolutely identical Josephson junctions cannot be prepared in different qubits, so that some scatter of the final parameters of ready qubits is inevitable. However, even in this case, one can expect the excitation of not only the modes of individual qubits but also synchronized collective modes induced by the interaction of qubits with each other via the electromagnetic field in the resonator. The theoretical description of possible processes under certain assumptions was presented in [5].

Figure 2 shows the signal amplitude for the structure under investigation versus the frequency and the magnetic field in the single-photon regime (achievable in our experiment at the total microwave power at the sample no higher than -130 dBm). The applied magnetic field is indicated in units of the current in the superconducting coil. As is seen in Fig. 2a, quasicrossings of the resonance frequencies of the qubits and the resonator frequency have a complicated structure owing to the interaction of the resonator with many qubits and the qubit–qubit interaction. Most interesting is a large gap in the spectral line of the resonator at coil currents of about ± 16 mA. In these regions, the energies of the states $|+, n\rangle$ and $|-, n+1\rangle$, where n is the number of photons in the resonator and $-$ and $+$ correspond to the ground and excited states of the mode, respectively, become degenerate. In such magnetic fields, a periodic exchange of energy between the collective mode of the qubits and the field in the resonator occurs. Thus, it can be concluded that, despite a large number of separate qubits in the resonator, there is a common resonance frequency of oscillations of the entire qubit array, which exhibits the same periodic dependence on the magnetic field as the frequencies of N individual qubits. The expected magnitude of this splitting in the resonator is $\sqrt{N}$ times greater than a similar crossing of an individual qubit [3]. This agrees with the properties of N noninteracting dipoles, whose coupling to the external resonator mode increases compared to the coupling constant of a separate dipole [6]. This effect previously observed for superconducting flux qubits [7] is a consequence of the Tavis–Cummings model [8] extending the Jaynes–Cummings model [9], which describes the interaction of an individual two-level system with a quantum mode in the resonator, to a large number of qubits. The expected dephasing rate of separate qubits in the present resonance regime is much higher than the coupling constant of an individual qubit to the resonator, $\Gamma_\phi \gg g$; hence, anticrossings of the levels of individual qubits from the cluster with the resonator mode can hardly be resolved against the background of noise and the line of the collective mode.

Figure 2a also demonstrates a peculiar structure of spectral lines in the zero-field region. This structure occurs because qubits have different frequencies owing to the scatter of the parameters of the Josephson junctions and two of them appeared to be very close to the resonator frequency. The microwave field at frequencies close to the resonator frequency directly excites these two qubits owing to their low detuning and sufficiently high coupling to the resonator. This allows the possibility of manipulating the collective state of the qubit array and its properties by a directed impact on separate qubits.

Two different types of anticrossings with the resonator levels become resolved with an increase in the excitation power (Fig. 2b). Small splittings can be attributed to crossing of the lines of individual qubits with the resonator line, whereas wider lines correspond to crossings of the resonator mode with the collective cluster state. This dissimilarity is most pronounced near coil currents of ± 13 mA: a broad spec-

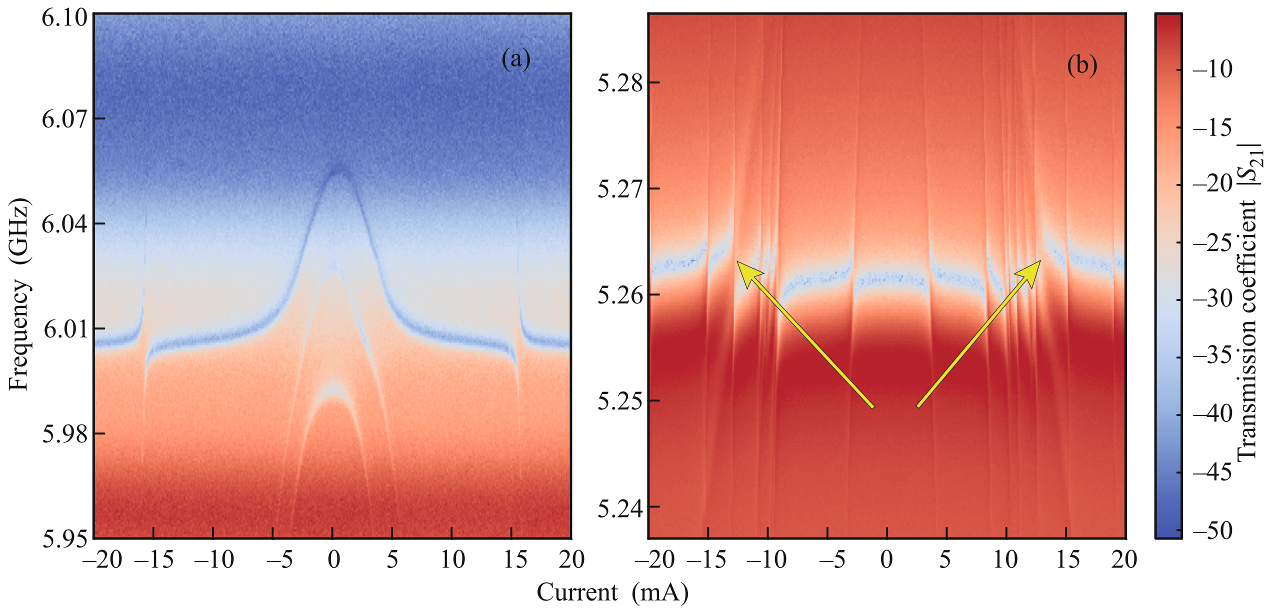

Fig. 2. (Color online) Amplitudes of the transmission signal through the resonators A and B versus the magnetic field applied to the sample and the frequency of the microwave signal. (a) Anticrossings of the fundamental mode of the resonator A and a cluster of 20 transmons in the single-photon regime (−130 dBm). One can see two symmetric splittings of the resonator frequency in the magnetic fields corresponding to coil currents of ±16 mA. At these points, the resonator frequency coincides with the frequency of the collective mode of the qubits, but the levels of both systems repel owing to the presence of interaction. The plot also shows the fragments of the spectra of two separate qubits (in the center), whose frequencies appear to be close to the resonator frequency owing to a scatter of the parameters of the Josephson junctions at the fabrication stage, so that these qubits are excited by the microwave signal swept through the resonator frequency separately from the cluster. Owing to the effect of these two qubits, the resonator frequency increases in the zero-field region. (b) The spectrum of anticrossings of the frequency of the resonator B and the cluster of 20 transmons at a higher microwave pumping power (−100 dBm) than in panel (a). Owing to its considerable inhomogeneous broadening, the mode corresponding to a collective state of the cubit cluster (indicated by arrows) can be distinguished from the anticrossings of the frequencies of individual qubits with the resonator mode.

tral line produces a large splitting of the resonator levels neighboring the interactions of individual qubits with the same resonator. A larger width of the spectral line of the collective mode implies that this mode has a shorter coherence time than individual qubits of the array. This can be explained by a stronger dephasing owing to the uncertainty in the number of photons of the coherent state of the resonator at a high radiation power and by the coupling constant $\tilde{g}$ between the field in the resonator and the collective mode of the qubit array that is larger by a factor of $\sqrt{N}$. The coupling constant $\tilde{g}$ can be computed from the spectrum in the same way as the coupling constant g between an individual qubit and the resonator. In the first-order perturbation theory, the minimum distance between the spectral lines can be found as

$$\Delta\omega = 2\tilde{g}\sqrt{n+1}, \tag{1}$$

where n is the number of a pair of dressed states (it is 0 in our case because the transitions from the ground state are observed). Since $\tilde{g}$ of the qubit array increases with the number of qubits as $\sqrt{N}$ [6], the resonator frequency shift at the level anticrossings point is also proportional to $\sqrt{N}$. Therefore, if the anticrossings for a separate qubit is also known, one can easily estimate the number of qubits in the cluster as the cluster-to-qubit splitting ratio squared.

The coupling constant g (determined by the splitting) for the anticrossings of individual qubits in Fig. 2b is about 5 MHz, whereas the coupling constant $\tilde{g}$ of the cluster state and the resonator is approximately 10–13 MHz. Hence, the effective number of qubits contributing to the enhanced splitting can be estimated as $N \approx 5$–7, which is smaller than 20, being a consequence of the scatter in the parameters of transmons on the chip and defect qubits.

The spectra of separate qubits of the metamaterial structure and the collective modes of the qubit array were also studied by two-photon spectroscopy. Figure 3 shows the transmission coefficient $|S_{21}|$ of the probe signal at the resonator frequency $\omega_R/2\pi$ versus the coil current inducing the magnetic field and the frequency of the second microwave mode with a high power (−100 dBm). There are a large number of spectral lines in the high-frequency region >7 GHz corresponding to the frequencies of both individual qubits and the qubit cluster as a whole (more intense lines). According to these data, the scatter of the qubit fre-

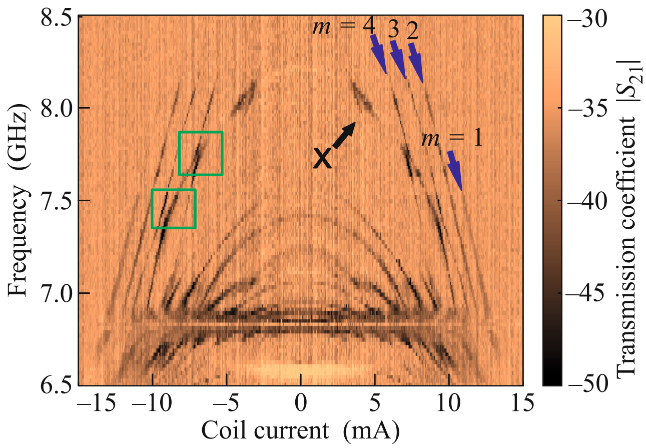

Fig. 3. (Color online) Spectra of the array of qubits in the resonator A at a high excitation power of $\simeq -100$ dBm at the chip. Green rectangles mark the regions with the interaction between an individual qubit and the qubit array. Blue arrows indicate the spectra corresponding to the frequencies of multiphoton transitions of the type $1/m(|0\rangle \to |m\rangle)$, where m is the number of photons and, simultaneously, the number of the qubit level. The m values are indicated next to the arrows. The horizontal spectral line at $\simeq$6.8 GHz belongs to an additional test resonator on the chip.

quencies is higher than 2 GHz. Figure 3 demonstrates nonlinear multiphoton effects responsible for the excitation of higher levels of the qubit array (the transitions $|0\rangle \to |2\rangle$, $|0\rangle \to |3\rangle$, etc.) that appear at a sufficiently high power of the signal scanning the sample. The modes $|0\rangle \to |m\rangle$ corresponding to these transitions are indicated in Fig. 3. Multiphoton transitions were previously observed for individual transmons in a resonator [10] and are intrinsic in this particular type of qubits owing to a low anharmonicity of their spectrum (about 5%). The transition $1/2(|0\rangle \to |2\rangle)$ of flux qubits [3] lies much higher in frequency than the transition between the ground and first excited states, and thus the frequency of the two-photon transition lies in another frequency range unachievable in the experiment. It is also worth mentioning an important feature of the lines corresponding to a collective state of qubits in Fig. 3: the signal at a frequency far from the resonator frequency $\omega_R/2\pi = 6$ GHz weakly excites the collective mode, which indicates that the qubits are coupled to each other via the resonator.

Figure 3 exhibits anticrossings of the levels of individual qubits with the collective mode of the qubit cluster (inside green rectangles). Owing to difference in magnetic-field dependence of the qubit frequencies and the existence of separate qubit and collective modes, a particular qubit (X) can be separated from the entire array and brought into the interaction with the common cluster mode. The magnitude of the level splitting decreases with an increase in the detuning Δ at the frequency crossing point. This confirms once more our assumption of the coupling of qubits via the resonator and the expected weakening of this coupling at an increase in the detuning. In the future, it would be interesting to study the possibility of transferring the excitation of an individual qubit to the cluster in such a system by exciting qubits by short microwave pulses. This approach opens the opportunity of making quantum memory with the use of large arrays of superconducting qubits.

To summarize, a coherent interaction of an array of transmon qubits with a resonator has been discovered. Collective modes of qubits appear to be stable in the regime of multiphoton transitions. The discovered interaction of a separate qubit with the collective mode of the qubit array opens the opportunity of storing an individual quantum state in the array, i.e., using the array as quantum memory.

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