Multiphoton transitions and light-dressing effects in the two-qubit system

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Strong interaction of a quantum system with light leads to various phenomena explained by resonant single- and multi-photon transitions between energy levels. We study effects of light-matter interaction that can occur in a system of two coupled transmons [1]. The transmon defines as a system with two Josephson junctions which are shunted by an additional large capacitance. This dc-SQUID setup allows for the tuning of the Josephson energy $E_J = E_{J,max}|\cos(\pi\frac{\Phi}{\Phi_0})|$ by means of an external magnetic flux Φ.

In our experiment, we observed the Autler-Townes [2] effect which is well-known in quantum optics. Earlier this effect was observed in atomic [3], molecular systems [4], quantum dots [5], and for superconducting qubits as well [6]. However, the previous studies have only involved just a single qubit system and have demonstrated only the standard spectral signatures known from the quantum optics. Considering this effect within a two-qubit system can be useful for studying the leakage problem.

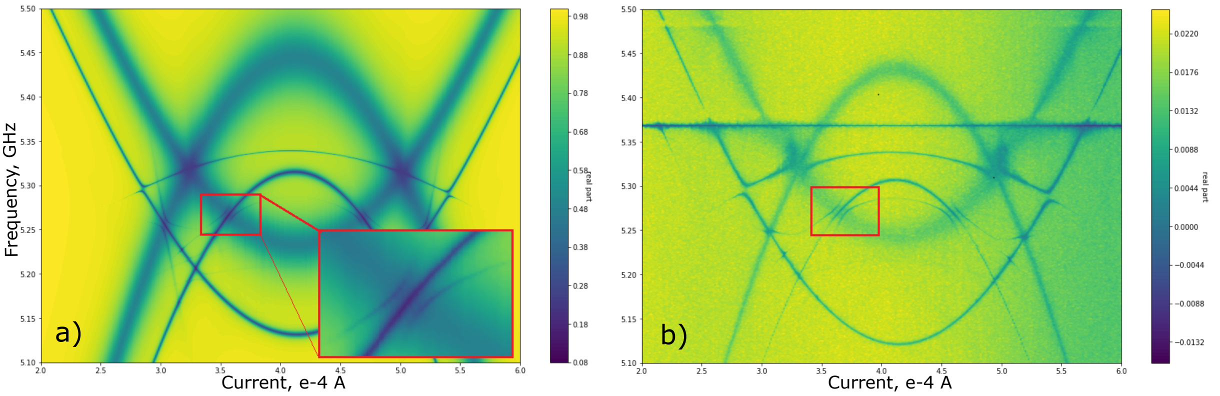

Figure 1: Two-tone spectroscopy of the our system: numerical modelling (a) and experiment (b). Shows dependence of qubits frequencies on the external magnetic flux. Colour shows the real part of complex transmission through the sample. In the highlighted area the splitting is caused by two-qubit Autler-Townes-like processes.

To investigate the two-qubit system we performed spectroscopic measurements and found remarkable features. Depending on the amplitudes of microwave drive the magnitude of splitting changed and we understood that the effect we observed was the Autler Townes effect. We carried out the numerical simulation which results is shown in fig. 1 (a). Also to find out the probability of transition (which were two-photon processes) we solved analytically the Hamiltonian of the system.

A single transmon can be considered as an oscillator with a quartic perturbation describing the leading-order anharmonicity. Therefore, we write down its Hamiltonian using the annihilation operator $\hat{b}$ ($\hbar = 1$):

$$\hat{H}_{tr} = \omega\hat{b}^\dagger\hat{b} + \frac{1}{2}\alpha\hat{b}^\dagger\hat{b}(\hat{b}^\dagger\hat{b} - 1),$$

where ω is its $|0\rangle \to |1\rangle$ transition frequency and α is the anharmonicity of the transmon. Additionally, by applying external magnetic flux Φ_e (via a control current) it is possible to control $\omega = \omega(\Phi_e)$. In our modelling, we take into account only the three lowest states of the transmon ($|0\rangle, |1\rangle$ and $|2\rangle$).

To induce state transitions in a transmon one should irradiate it by a monochromatic microwave signal of frequency ω_d using a capacitively coupled transmission line. The interaction term between the transmon and the field is then modelled by the following operator:

$$\hat{H}_d = \Omega(\hat{b} + \hat{b}^\dagger)\cos\omega_d t,$$

where Ω stands for the frequency of the Rabi oscillations between $|0\rangle$ and $|1\rangle$.

Now, the complete Hamiltonian of system contains two terms describing each of them in isolation (with the corresponding annihilation operators $\hat{b}$ and $\hat{c}$, the $|0\rangle \rightarrow |1\rangle$ transition frequencies $\omega_{1,2}$ and anharmonicities $\alpha_{1,2}$), two terms representing the interaction of each transmon with the driving field with frequencies $\omega_{d1,2}$, and the transmon-transmon interaction term:

$$\hat{H} = \hat{H}_{tr1} + \hat{H}_{tr2} + \hat{H}_d^1 + \hat{H}_d^2 + \hat{H}_{int},$$

where $\hat{H}_{int} = J(\hat{b} + \hat{b}^\dagger)(\hat{c} + \hat{c}^\dagger)$ is the transverse interaction between transmons.

To solve the Schrodinger equation* we moved to the rotating frame, which rotates with the first driver. Then found the first-order correction to eigenstates using the interaction term as a perturbation for hamiltonian $\hat{H}^R = \hat{H}_{tr1}^R + \hat{H}_{tr2}^R + \hat{H}_d^{1R}$. Finally, we used two-photon Fermi Golden rule to found the probabilities for time-dependent perturbation $\hat{H}_d^{2R}$.

References

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