Absorption spectra of superconducting qubits driven by bichromatic microwave fields

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Introduction

An experimental observation was reported of two distinct quantum interference patterns in the absorption spectra when a superconducting transmon qubit is subjected to a bichromatic microwave field with the same Rabi frequencies. The results show good agreement between the numerical simulation and experimental data. Such multiphoton interference may be used in manipulating the quantum states and/or generate nonclassical microwave photons.

Experimental set-up with **Triton 500 Cryofree** dilution refrigerator

Superconducting qubits are one of the most promising candidates for the implementation of circuit quantum electrodynamics (QED) platforms. The coupling of the system with driving fields has proven to have a high potential for scalability. Superconducting qubit architectures, which interact with the external field couplings, have been extensively studied.

In this work, we reveal the nonlinear dynamical level splitting of superconducting circuits driven by a bichromatic microwave field. The external field possesses two equal amplitude components with frequencies scanned from large detuning to resonance frequencies. We focus on the near-resonance frequencies where subharmonic resonances generate fringe patterns in the transition probability spectra. We also demonstrate these results theoretically.
can be used as a measure of the quality of this interface. At low temperatures the superconducting electrodes induce superconductivity in the topological insulator by the proximity effect, with a finite Josephson current observed across a sufficiently narrow gap.

Experiment

Our device consists of a superconducting transmon qubit coupled to a three-dimensional aluminum cavity. The length, width, and depth of the cavity are 15.5, 4.2, and 18.6 mm, respectively. The transmon is made via electron beam lithography and double-angle evaporation, in which a single Al/AlOx/Al Josephson junction is capacitively shunted by two Al pads on a high-resistance Si substrate. The schematic of the experimental setup is shown in Figure 1. The device is located in an Oxford Triton 400 dilution refrigerator below 20 mK with magnetic shielding. The microwave lines to the cavity are heavily attenuated at each stage of the dilution refrigerator and sent to the cavity through low-pass filters with a cutoff frequency of 12 GHz. The output signal from the cavity is passed through cryogenic circulators and a high-electron-mobility transistor (HEMT) amplifier located in the dilution refrigerator and further amplified at room temperature. It is then mixed down and digitized by a data acquisition card.

Three microwave drives are used in the experiment. Qubit control waves (denoted as probe and coupler) are continuous while the readout wave (denoted as cavity) is triggered. Cavity, probe, and coupler waves are combined by two power splitters at room temperature before being sent to the dilution refrigerator. In a sampling period, the cavity wave is turned on at time t = 70 ns for 2100 ns and the data acquisition card starts to record at time t = 270 ns. The repetition rate is 10 kHz so the whole sequence is repeated every 100 μs.

The states of the transmon are measured by using a Jaynes-Cummings readout. The cavity wave is applied at the bare cavity frequency $\omega cav/2\pi$ = 10.678 GHz. We obtain the transition resonance frequency $\omega ge/2\pi$ = 8.865 GHz and $\omega ef /2\pi$ = 8.637 GHz from the spectrum, from which we get the Josephson energy EJ/h = 45.33 GHz and the charging energy Ec/h = 228 MHz. Using the pump-probe method we obtain the energy relaxation time T_1 = 0.53 μs. The spin-echo measurement shows the dephasing time T_2 = 0.51 μs.

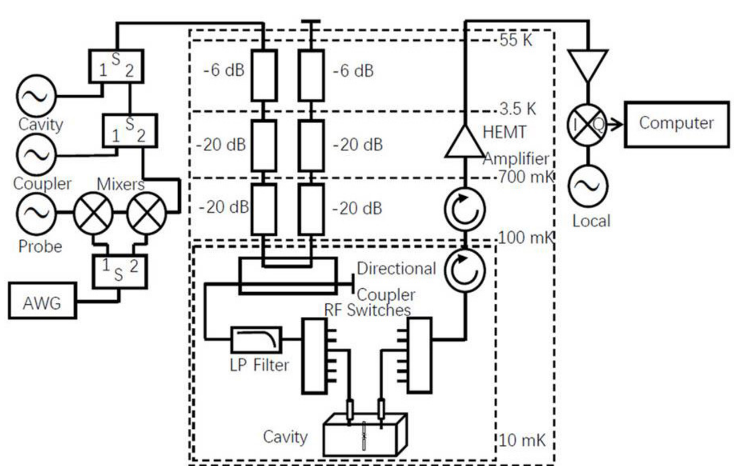

Figure 1. Circuit diagram of set-up. Attenuators, filters, and circulators are used to reduce the external noise. The output signal is then amplified and down-converted with a local oscillator and digitized.

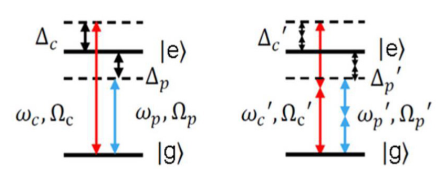

Figure 1. Energy level and microwave drive diagrams represent one-photon transition (left) and two-photon transition (right), respectively.

Experimental results

To demonstrate the effect of two near-resonance microwave fields driving, the probe and coupler waves are turned on continuously, so the system stays at a steady state during the measurement. By sweeping both $\Delta p = \omega p - \omega ge$ and $\Delta c = \omega c - \omega ge$ (which are the detunings of the probe and coupler, respectively) around zero, we measure the spectrum of the qubit. As illustrated in Figure 2, in the one-photon transition experiment, the coupler frequency ωc and the probe frequency ωp are both near the transition resonance frequency ωge, and the coupling strengths are $\Omega c/2\pi = \Omega p/2\pi = 4.16$ MHz. In the two-photon transition experiment, $\omega' c$ and $\omega' p$ are near $\omega ge/2$ and $\Omega' c/2\pi = \Omega' p/2\pi = 0.973$ MHz.

The experimental and theoretical transition probabilities are presented in Figure 3, when a transmon superconducting qubit is subject to two near-resonance to resonance microwave fields. Figure 3(a) and 3(b) correspond to the case when the single-photon transition condition is satisfied. In this case, absorption spectrum near the single-photon resonance can be produced by transverse and/or longitudinal coupling between a two-level system. Figure 3(c) and 3(d) present the experimental and theoretical results for the observation of the two-photon transitions. In this case absorption spectrum near the two-photon resonance can only be produced by a longitudinal coupling between the qubit and the bichromatic microwave field. The results show good agreement between the numerical simulation and experimental data.

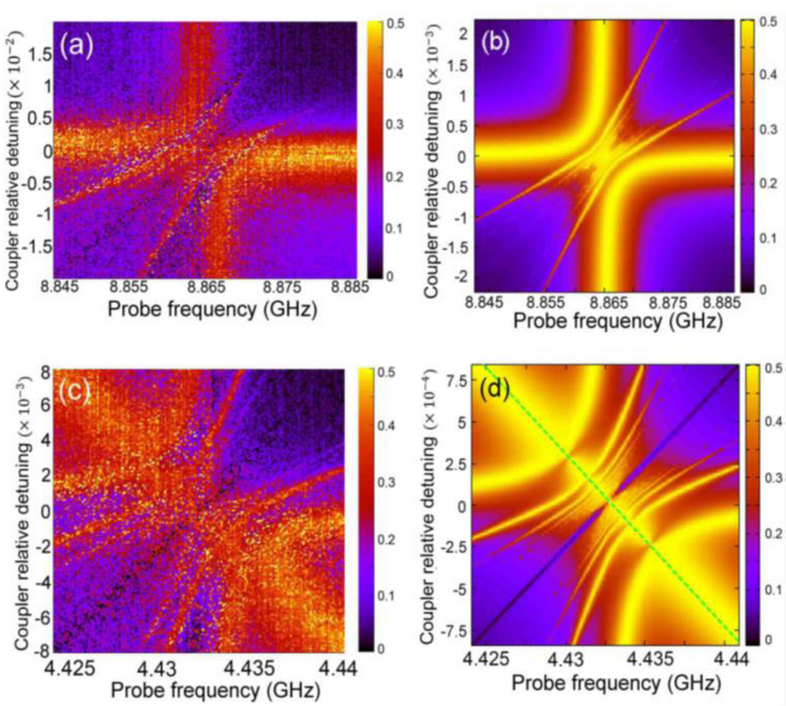

Figure 3(a) Experimental measurement (b) theoretical result of the single-photon transitions in a superconducting transmon qubit. (c) Experimental measurement (d) theoretical result of the double-photon transitions in a superconducting transmon qubit.

Conclusion

In summary, we report experimental observation of two distinct quantum interference patterns in the absorption spectra when a superconducting transmon qubit is subject to a bichromatic microwave field.

The results show good agreement between the numerical simulation and experimental data. These observations and interpretation may be used not only to generate multilevel tunable energy structures, but also to explore nonclassical microwave photons, which are the fundamental elements in quantum information processing, especially in microwave quantum photonics.

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