Superconducting non-linear resonator for non-destructive readout of a flux qubit

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Abstract. We have investigated microwave response of a $\lambda/4$ superconducting coplanar waveguide resonator which is terminated by a DC-SQUID coupled with a flux qubit. The circuit is designed for non-destructive single-shot readout of a flux qubit based on dispersive interaction between the qubit and the resonator and switching between bistable states of the driven nonlinear resonator. A high-frequency ($\sim 10$ GHz) resonator is exploited for suppressing photon-number fluctuations which cause qubit dephasing even when the readout circuit is not activated. We observed bifurcation of the resonator in the nonlinear driving regime. In the linear regime, the degeneracy point of the qubit was detected as a shift of the resonant frequency.

1. Introduction

A high-fidelity single-shot readout of a qubit is crucial in many experiments related to quantum information processing. For Josephson-junction qubits, fidelities of about 90% have been achieved [1, 2] and are expected to be improved.

Another important figure of merits in qubit readout is the smallness of the back-action. In an ideal measurement, the qubit state after the readout would be projected to an energy eigenstate which will not evolve further in time (except for the global phase in the wave function). This means that the information obtained and the state left are perfectly correlated, and thus, the qubit remains in a pure state. In reality, however, back-action of the readout detector often disturbs the state by inducing transitions between the eigenstates, which results in a mixed state. Moreover, it often affects the state of the neighboring qubits as well, which would be harmful for quantum error correction where a result of the readout should be feed-backed to other qubits coherently evolving. For example, such problems exist in current-biased SQUIDs which have been commonly used as a readout device of a flux qubit [3]. When the SQUID switches to the voltage state, it locally generates high-frequency voltage noise due to the Josephson oscillations as well as quasiparticles dissipating a large amount of energy.

Non-destructive readout of Josephson-junction qubits has been implemented in circuits where the qubit is dispersively interacting with a superconducting resonator. While the resonator does not exchange energy with the qubit far detuned, the dispersive interaction gives rises to a measurable shift of the resonant frequency. Such measurement was first achieved in a linear

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resonator in a weak driving power limit [4]. Use of a driven nonlinear resonator relaxes the strong demand of the low-noise broadband microwave measurement in the linear regime: The latching effect between the bifurcated dynamically stable states gives a larger but still fast response [5]. Applications of such schemes on charge qubits [6, 7, 8] and flux qubits [1, 9, 10, 11] have been reported. For the nonlinear resonators, Josephson junctions as nonlinear inductors and lumped-element capacitors have been often employed, and their resonant frequencies were typically around 1 GHz [1, 6, 7, 9, 10, 11]. In general, however, using a distributed element such as coplanar waveguide (CPW) makes it easier to achieve a higher resonant frequency and a higher quality factor, which has been demonstrated for a charge-qubit readout [8].

We have been studying a microwave circuit where a flux qubit is coupled to a DC SQUID which is terminating a superconducting CPW resonator. The circuit is designed for non-destructive single-shot readout of a flux qubit based on dispersive interaction between the qubit and the resonator and switching between bistable states of the driven nonlinear resonator. A high-frequency (∼ 10 GHz) resonator is exploited for suppressing photon-number fluctuations which cause qubit dephasing even when the readout circuit is not activated. The resonant frequency much higher than the qubit frequency as well as the high quality factor would be also helpful in suppressing qubit relaxation through the resonator [12]. We are also motivated in the readout of the qubit biased at the degeneracy point where the symmetry protects the qubit further from the relaxation and the dephasing.

2. Sample and experimental setup
The sample is composed of an Al flux qubit coupled to an Al DC-SQUID which is terminating a Nb CPW resonator. The Nb CPW resonator was patterned by photolithography and SF₆ reactive ion etching; a 50 nm thick Nb film sputtered on a 300-μm thick Si wafer covered by 300-nm thick thermal oxide was used. The Al parts were fabricated by electron-beam lithography and shadow evaporation technique. In order to realize a superconducting contact between Nb and Al, the surface of Nb was cleaned by Ar⁺ milling before the Al evaporation.

The λ/4 Nb CPW resonator consists of a center conductor (10-μm wide and 2.76-mm long) and two lateral ground planes nearby, and is terminated by an Al DC-SQUID. We aimed to obtain the resonant frequency \( f_r \sim 10 \text{ GHz} \) and the quality factor \( Q \sim 10^3 \); the latter requires coupling capacitance \( C_C \) of ∼ 8 fF. The critical current of the DC-SQUID was estimated to be 5.5 μA per junction from the test measurement. The self inductance of the SQUID is estimated to be 89 pH by a numerical calculation. The flux qubit has four Josephson junctions, and one

![Figure 1](image-url)

**Figure 1.** (a) Schematic diagram of the measurement setup and the sample structure. (b) Phase of the reflection coefficient \( \Gamma \) as a function of the frequency. Measurement was done at zero flux bias and in the linear driving regime at \( P_{in} = -60 \text{ dBm} \).
Figure 2. (a) Phase of the reflection coefficient $\Gamma$ as a function of the microwave frequency $f$ at the power level of $P_{\text{in}} = -28.4$ dBm. The arrows show the sweep directions. (b) Positions of the phase jumps in the $\Gamma$ vs. $f$ curves for various $P_{\text{in}}$, plotted on the $f$--$P_{\text{in}}$ plane. Red circles (right branch) and blue circles (left branch) were obtained by sweeping up and down the frequency, respectively. The dashed line indicates the power and the frequency range used in Fig. 2(a).

The field for the dc flux bias was applied by a superconducting solenoid, which is located beneath the sample package. All measurements were done using a dilution refrigerator at the base temperature of 30 mK. Figure 1(a) shows a schematic diagram of the measurement setup. To measure the reflected signals from the resonator, the output line is isolated from the input line by a directional coupler. A cryogenic HEMT amplifier with a gain of 38 dB and a noise temperature of 9 K is connected to the output line at 4.2 K. We measured the reflection coefficient $\Gamma$ of the resonator using a vector network analyzer connected to the “IN” and “OUT” ports in Fig. 1(a).

3. Results and discussion

First we characterized the resonator in the linear regime. Figure 1(b) shows the phase of $\Gamma$ as a function of the frequency. The data was taken at zero flux bias and at $P_{\text{in}} = -60$ dBm, where $P_{\text{in}}$ is the input power from the network analyzer. A $2\pi$ rotation is observed as expected for a reflection-type resonator; note that Fig. 1(b) shows the vicinity of the resonant frequency $f_r$ only. From the frequency dependence of $\Gamma$, we obtain $f_r = 9.635$ GHz and $Q = 1.4 \times 10^3$, which are consistent with our designs.

Next we drove the CPW into the nonlinear regime. Because of the nonlinearity of the Josephson inductance of the DC-SQUID, $f_r$ gradually decreases as the drive power $P_{\text{in}}$ is increased. When we increase $P_{\text{in}}$ further, the phase shows an abrupt jump. In addition, the position of the jumps are not necessarily the same when the direction of the frequency sweep is reversed. The hysteresis observed in Fig. 2(a) manifests the existence of two stable states in the driven resonator. The positions of the jumps for various values of $P_{\text{in}}$ are plotted in Fig. 2(b).

A periodic modulation of the resonant frequency in the linear regime was observed when the external flux bias was swept, as shown in Fig. 3, where the direction of the flux sweep was from left to right. This modulation is caused by the periodic modulation of the Josephson inductance of the DC-SQUID under the magnetic field. The big discontinuities are due to the fact that the SQUID has a finite loop inductance which is not negligible compared to the Josephson inductance. The global flux bias in Fig. 3 is represented by $\Phi/\Phi_0$, where $\Phi$ is the qubit flux bias, and $\Phi_0 = h/2e$ is the magnetic flux quantum. When the flux is swept across the points
Figure 3. Modulation of the resonant frequency $f_r$ with external dc flux bias. The global flux bias is represented by a flux $\Phi$ through the qubit loop. The flux qubit was detected as a shift of $f_r$ at $\Phi/\Phi_0 = \pm 0.5$, as indicated by dashed circles. The input microwave power to the resonator was $-60$ dBm. The direction of the sweep was from left to right.

$\Phi/\Phi_0 = \pm 0.5$, a small step in $f_r$ is seen. The step indicates that at the flux bias qubit persistent current in its ground state changes directions.

4. Conclusion
We studied microwave response of a superconducting CPW resonator terminated by a DC-SQUID to which a flux qubit is coupled. In the nonlinear regime, we observed bifurcation of the reflected microwave signal. The flux-dependent resonant frequency in the linear regime revealed steps corresponding to the change of the persistent current in the qubit ground state at the degeneracy point. The application of the switching between the bifurcated states to non-destructive single-shot readout of a flux qubit is being investigated.

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