Measuring the decoherence of a quantronium qubit with the cavity bifurcation amplifier

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Dispersive readouts for superconducting qubits have the advantage of speed and minimal invasiveness. We have developed such an amplifier, the cavity bifurcation amplifier (CBA), and applied it to the readout of the quantronium qubit. It consists of a Josephson junction embedded in a microwave on-chip resonator. In contrast with the Josephson bifurcation amplifier, which has an on-chip capacitor shunting a junction, the resonator is based on a simple coplanar waveguide imposing a predetermined frequency and whose other rf characteristics such as the quality factor are easily controlled and optimized. Under proper microwave irradiation conditions, the CBA has two metastable states. Which state is adopted by the CBA depends on the state of the quantronium qubit coupled to the CBA’s junction. Due to the megahertz repetition rate and large signal to noise ratio, we can show directly that the coherence is limited by $1/f$ gate charge noise when biased at the “sweet spot”—a point insensitive to first order gate charge fluctuations. This architecture lends itself to scalable quantum computing using a multiresonator chip with multiplexed readouts.

INTRODUCTION

Quantum circuits based on Josephson junctions are candidates for the fundamental building block of a quantum computer—a quantum bit, or qubit. Several implementations have been tested, which may be distinguished by the vari-
dates for the fundamental building block of a quantum

(Pb, Q)

ducting resonator. With this architecture, we can measure

able readout system based on a driven nonlinear supercon-

ing, and the technique used for the readout. These systems can be

individual addressed, controlled, and read, making them

some of the most advanced solid state qubits.

An enabling characteristic of many superconducting qu-

bits is the existence of an optimal bias point where the qubit

is immune to first order to fluctuations in external control

parameters. Nonetheless, even systems operated at this “sweet spot” have coherence times limited by second order fluctuations of the external control parameters. In this paper we describe measurements of a quantronium qubit operated at this optimal bias point, employing the recently developed cavity bifurcation amplifier (CBA)—a fast, dispersive, scalable readout system based on a driven nonlinear superconducting resonator. With this architecture, we can measure the fluctuations in the quantronium’s coherence on time scales as short as a second, allowing us to probe the $1/f$ property of charge noise on these scales. These measurements confirm previous studies of the limitations of coherence times in charge qubits and cast additional light on the fluctuating character of $T_2$ itself and how its value depends on the measurement protocol.

The nonlinearity of the CBA is provided by a Josephson junction placed in the center of a λ/2 on-chip coplanar waveguide resonator with both an input and an output coupling capacitor playing the role of Fabry-Pérot cavity mirrors (see Fig. 1). When driven with a microwave signal at frequency $\nu_j$ such that $\nu_j < \nu_0(1 - \sqrt{3}/Q)$, where $\nu_0$ is the resonator small oscillation natural frequency and $Q$ the loaded quality factor, this system can have two dynamical metastable states which differ by their oscillation amplitude and phase. As the driving power $P$ is ramped past the bifurcation power $P_b$, the CBA switches from the state of low amplitude (to the state with high amplitude. We detect the state of the nonlinear oscillator by monitoring the amplitude and phase change of the microwave signal transmitted by the resonator. In parallel with the CBA’s junction, we place a split Cooper pair box (SCPB), a circuit known as the quantronium, giving

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the resonator two bifurcation powers $P_b^0$ and $P_b^1$, depending on the state of the qubit, $|0\rangle$ or $|1\rangle$. The two qubit states are mapped into the two metastable states of the CBA by ramping quickly the power $P$ to a level intermediate between $P_b^0$ and $P_b^1$. If the quantronium qubit is in $|1\rangle$, the CBA will switch to the high oscillating state, whereas if it is in $|0\rangle$, the CBA will remain in the low oscillating state.

FIG. 1. (Color online) (a) Scanning electron micrograph of a duplicate of the measured device, both of which are fabricated on the same chip simultaneously. (b) Schematic of our sample and its environment. The sample consists of a split Cooper pair box whose loop is interrupted with a large junction (quantronium). The state of the quantronium alters the switching probability $P_{01}$ of the CBA between its two metastable states, which can be inferred from the amplitude and phase change of transmitted microwave pulses through the device.
This readout has the advantage of being nondissipative as the readout junction never switches into the normal state, unlike the original dc-biased quantronium readout. This dispersive readout minimally disturbs the qubit state and since after switching we do not need to wait for quasiparticles to relax, the repetition rate is only limited by the relaxation time $T_1$ of our qubit and the $Q$ of our resonator. Like the dc readout, the CBA readout can latch, allowing enough time for the measurement of the complex amplitude of the transmitted wave and therefore excellent signal to noise ratio. These characteristics were also present in the Josephson bifurcation amplifier, which implemented a bifurcating nonlinear oscillator using a lumped element capacitor in parallel with the junction. However this capacitor was fabricated using a Cu/Si$_3$N$_4$/Al multilayer structure, which was difficult to fabricate and integrate with more than one qubit. Also, the parallel plate geometry suffered from inherent stray inductive elements. In contrast, the CBA is fabricated using a simple coplanar waveguide (CPW) geometry with no stray elements. The resonance frequency $v_0$ and the quality factor $Q$ are controlled by the resonator length and output capacitor, respectively. The CBA geometry thus offers the possibility of designing a multiresonator chip with multiplexed readouts, which would accommodate up to ten qubits at once, an important step toward scalable quantum computing. The new architecture, is a first step in this direction.

**SAMPLE FABRICATION AND CHARACTERIZATION**

The resonator is initially fabricated using photolithography on a bare Si wafer. A LOR5A/S1813 optical resist bilayer is used and the development is optimized to have at least 50 nm of undercut beneath the S1813 to avoid wavy edges and to obtain a sloped edge on the resonator. This sloped edge is obtained by evaporating a 200 nm thick Al layer onto the sample at 0.2 nm/s with an angle of 5° and with a stage rotation of 10°/s. Next, the quantronium is fabricated using electron beam lithography. We use a MMA/PMMA resist bilayer and the Dolan bridge double angle evaporation technique to fabricate our junctions. For this sample, the split Cooper pair box is fabricated first inside the resonator, followed by the readout junction in a separate step using a new e-beam resist. Using a hollow cathode Ar ion gun, we obtain an Ohmic contact between the two e-beam layers and the resonator.

For the qubit sample described in this paper, we have been working with a linear regime resonance frequency $v_0 = 9.64$ GHz and a $Q$ of 160. An on-chip twin of the SCPB of the quantronium had a normal state resistance of 15 kΩ, with small junction areas of 0.05 μm$^2$. The usual gate line of the quantronium is absent in our design since we use the readout lines to access both the rf and dc gate lines, another advantage of this configuration.

**QUBIT CHARACTERIZATION**

We performed gate charge and flux modulations while keeping the qubit in its ground state, to check that we have flux periodicity and 2e charge periodicity, as shown in Fig. 2. The readout was first operated in the weakly nonlinear mode ($P \ll P_b^{\text{lin}}$) and we measured changes in the phase of the transmitted signal or its double, an effect similar to that observed by Wallraff et al. Using the well-known expressions for the energy levels of the quantronium, we can reproduce the shape of these contours, within the uncertainty due to the low frequency gate transition frequency coinciding with the readout frequency or its double, an effect similar to that observed by Wallraff et al. Using the well-known expressions for the energy levels of the quantronium, we can reproduce the shape of these contours, within the uncertainty due to the low frequency gate charge and flux noises, and extract a Josephson energy of the SCPB $E_J$ of 15 GHz and charging energy $E_{CP}=(2e)^2/2C_S$ of 17 GHz, where $C_S$ is the sum of the capacitances of the junctions in the SCPB and the gate capacitance.

To get a more precise measurement of $E_J$ and $E_{CP}$, we performed spectroscopy on the qubit by applying a weakly exciting 1 μs long pulse, followed by a latching readout pulse. The switching probability $P_{\text{on}}$ between the two metastable states of the CBA is measured as the spectroscopic frequency $v_s$ is swept for each gate charge step, at zero flux. Due to the cross-talk between the readout and the qubit, we have to ensure that we have zero leakage of spectroscopic power outside our pulse. This is achieved by gating the LO on the mixers shaping our pulses, with a pulse shape which is a few nanoseconds longer than the spectroscopic pulse. As a function of frequency, we find a peak in the switching probability, whose position varies with gate charge with the expected sinusoidal-like shape shown in Fig. 3. The theoretical fit, shown in red, refines the previous determination of $E_J$ and $E_{CP}$ to the values $E_J=15.02$ GHz and $E_{CP}$...
MEASURING THE DECOHERENCE OF A QUANTRONIUM... PHYSICAL REVIEW B 76, 174516 (2007)

FIG. 3. (Color online) Spectroscopy peak as a function of gate charge \(N_g\). Staying at zero flux, we measure \(P_{01}\) while sweeping \(v_g\) and stepping \(N_g\). The theoretical fit of the resulting sinusoidal-like dependence of the peak with \(N_g\) is given by the red dashed line with the fit parameters \(E_J=15.02\) GHz and \(E_{CP}=17.00\) GHz. The vertical lines with no \(N_g\) dependence are the excitations between qubit energy levels endowed at multiples of the readout frequency, similar to those seen in Fig. 2.

\[ = 17.00 \text{ GHz}. \]

Zooming in to the double sweet spot, \(N_g=0.5\), \(\Phi/\Phi_0=0\), where the qubit is immune to charge and flux noise to first order, we measure a Lorentzian spectroscopic peak of width \(\Delta v_{01}=2.6\) MHz and a Larmor frequency \(v_{01}=14.35\) GHz. This gives a dephasing time, \(T_2=1/\pi \Delta v_{01}\), of 120 ns. However, large charge jumps move the biasing point off the sweet spot causing the linewidth to be widened. More accurate measurements of \(T_2\) will be obtained from Ramsey fringes where we can follow the variation of \(T_2\) with time.

QUBIT MANIPULATION AND COHERENCE EXPERIMENTS

Once the qubit parameters are known, we can perform experiments on the qubit to determine the qubit’s quality in terms of its energy relaxation time \(T_1\) and dephasing time \(T_2\). An essential part of these experiments is the need to control the state of the qubit precisely. This is achieved by applying a microwave pulse to the gate with rectangular envelope of amplitude \(A\) and time length \(\tau\). In a frame rotating at the gate pulse carrier frequency \(v_p\), the qubit state then precesses at a frequency, \(v_p\), given by

\[
u_p = \left( (v_{\text{Rabi}})^2 + (v_{01} - v_p)^2 \right)^{1/2},
\]

where the Rabi frequency \(v_{\text{Rabi}} = 2E_C G A N_g \langle 0|N|1 \rangle /h\) involves the gate modulation amplitude in units of Cooper pairs \(\Delta N_g = C_p A/2e\) and charge operator matrix element between the excited and ground states \(\langle 0|N|1 \rangle \). For \(A=0\), we have free evolution at the Ramsey frequency \(v_{\text{Ramsey}} = |v_{01} - v_p|\).

We begin by measuring the Rabi oscillations. The pulse sequence protocol involves a gate pulse with fixed \(v_g = v_{01}\) and varying amplitude \(A\) and time length \(\tau\) followed by a latching readout pulse. The sequence is repeated \(10^4\) times to measure the switching probability. The oscillations of the switching probability as a function of \(\tau\) and \(A\) are plotted in

FIG. 4. (Color online) (a) Rabi oscillations in the switching probability \(P_{01}\), as a function of gate charge modulation \(\Delta N_g\) and gate pulse time length \(\tau\). \(\Delta N_g\) is calculated from the Rabi pulse envelope voltage \(A\) reaching the sample through the attenuation in the input lines and is plotted in terms of Cooper pairs, \(\Delta N_g = C_p A/2e\). Oscillations in the switching probability \(P_{01}\) are seen with both \(\Delta N_g\) and \(\tau\). (b) Fitted Rabi frequency \(v_{\text{Rabi}}\) vs \(\Delta N_g\). As expected from a two-level system, \(v_{\text{Rabi}}\) scales linearly with \(\Delta N_g\).

Fig. 4. The extracted frequency \(v_{\text{Rabi}}\) scales linearly with \(\Delta N_g\) [Fig. 4(b)] as expected from a two-level system. From the position of the first maximum of the Rabi oscillations, we can calibrate the pulse time length needed for a \(\pi\) pulse, which drives the qubit from the ground state to the excited state. Using this \(\pi\) pulse, we measure the exponential decay of the population of the excited state (data not shown) and obtain the relaxation time \(T_1\) during the course of an experimental run, varied between 1.4 and 1.8 \(\mu s\), with a persistence time of a few seconds. These values are comparable to the results of Vion et al. and Siddiqi et al.

The maximum contrast measured is about 60%, lower than the maximum contrast of over 99.9%, calculated for the ideal case of a nonrelaxing qubit given the measured parameters of the resonator. This loss can be attributed to three main sources. First, the qubit relaxes before the readout takes place because of its finite \(T_1\), resulting in a 10% loss in contrast. Second, the qubit relaxes to the ground state as the readout voltage approaches the bifurcation voltage, resulting in a further 25% loss in contrast. Other measurements (not described here) have suggested that this loss in contrast could be from Stark shifting the qubit to lower frequencies during readout, where it can come in resonance with spurious transitions, possibly due to defects in the substrate or in the tunnel barrier. The remaining loss could be accounted for by the fact that the transition between the two oscillating states of the CBA is broadened by more than a factor of 5 from that expected.

To measure the coherence time, \(T_2\), we follow a different pulse protocol in which we apply two \(\pi/2\) pulses separated...
They each take 0.35 s to acquire. We can see visually the variation of in the fringes near 1 \( \mu \)s, similar to the first Saclay result obtained with a sequence compensates for decoherence due to low frequency fluctuations. However, we expect that charge noise is Gaussian with a spectral density that has the usually invoked 1/f form given by \( S_\alpha(\omega) = \alpha^2 / |\omega| \). In the simulation, we used ten times more points compared to the data to obtain a smoother curve. (d) Corresponding distribution of Ramsey frequencies at four different flux biasing points. Each distribution has 3000 Ramsey traces. The blue histogram corresponds to the data in (a), (b), and (c). The Ramsey frequency is extracted from the position of the maximum of the power spectral density of each decaying sinusoid. The distributions are lopsided to higher frequencies as would be expected from fluctuations in the gate charge around our operating point at the sweet spot. The expected distribution assuming the same 1/f charge noise as in (c) is shown in Fig. 5(b). By fitting to an exponentially decaying sinusoid, we extract an individual measured frequency of Ramsey fringes is well fitted by the absolute value of the detuning \( |\nu - \nu_0| \), yielding a precise measurement of \( \nu_0 = 14.346 \text{ GHz} \). We follow the time evolution of \( T_2 \) and \( \nu_0 \) by recording a Ramsey fringe every 0.35 s [Fig. 5(a)]. We observe stochastic fluctuations of \( T_2 \) with an asymmetric bell shaped distribution peaking around 600 ns, with a long tail extending down to 150 ns [Fig. 5(c)]. If we would average over 3000 above Ramsey traces (17.5 nm period), we would measure an average \( T_2 \) which converges to 500 ns, similar to the first Saclay result obtained with a qubit with a similar \( E_j / E_{CP} \). Note that a Hahn spin echo sequence compensates for decoherence due to low frequency variations of the qubit transition frequency. However, we intentionally perform the standard Ramsey fringe protocol as a manner of studying these low frequency fluctuations and determining their source. The \( T_2 \) fluctuations are correlated with fluctuations in the Ramsey frequency, which only fluctuates toward higher frequencies, giving lopsided distributions, as shown on Fig. 5(d). At the sweet spot where we are working, variations in gate charge necessarily increase the transition frequency, whereas variations in flux decrease it. Variations in critical current would supposedly keep the distribution of frequencies more symmetric. We can therefore conclude that charge noise, not flux noise, is the dominant source of decoherence in our sample. Furthermore, if we suppose that the charge noise is Gaussian with a spectral density that has the usually invoked 1/f form given by \( S_\alpha(\omega) = \alpha^2 / |\omega| \), we can check if our data can be explained by this model. This was carried out by directly numerically simulating the corresponding variations in transition frequency and calculating the Ramsey signal in the conditions of the experiment. The distributions of both the extracted \( T_2 \) and \( \nu_\text{Ramsey} \) are shown by the dashed lines in Figs. 5(c) and 5(d). We obtain good agreement with the data for a noise amplitude of \( \alpha = 1.9 \times 10^{-2} \), agreeing with the range of previously measured values of this noise intensity parameter. To reduce sensitivity to this charge noise, we can make the energy levels of the qubit almost insensitive to charge by increasing \( E_j / E_{CP} \). This is achieved by increasing the areas of the two sides of the CPB or by increasing the capacitance of the island to ground. An \( E_j / E_{CP} \) of 8 could give a \( T_2 \) in the millisecond range and hence this device would be \( T_1 \) limited.

**CONCLUSION**

We have successfully implemented an improved version of the bifurcation amplifier based on an on-chip CPW resonator as a readout for the quantronium qubit. It offers ease of fabrication and a larger range of operating parameters \((\alpha_0, Q)\) compared to the original JBA implementation. Using this readout which captures in real time the fluctuations...
in qubit parameters, we have demonstrated that the main source of decoherence in our sample is charge noise. By using a larger $E_j/E_{CP}$, we could reduce the curvature with gate charge of the levels of the Cooper pair box and we should be able to reduce the charge noise induced decoherence. Furthermore, the CBA geometry is particularly well adapted to the multiplexing of the simultaneous readout of several qubits. We have started in this direction by successfully measuring the bifurcation of five CBAs with only one input and one output line. This configuration offers a path for scaling up of superconducting circuits up to several tens of qubits. Furthermore, cavity bifurcation amplification has further applications outside the realm of superconducting qubits, particularly in the measurement of any phenomenon that can be coupled to the Josephson energy.

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\[\text{(9) G. Ithier et al., Phys. Rev. B 72, 134519 (2005).}
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\[\text{(11) E. Boaknin, V. E. Manucharyan, S. Fissette, M. Metcalfe, L. Frunzio, R. Vijay, I. Siddiqi, A. Wallraff, R. J. Schoelkopf, and}
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