Fast Reset and Suppressing Spontaneous Emission of a Superconducting Qubit


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Spontaneous emission through a coupled cavity can be a significant decay channel for qubits in circuit QED. We present a new circuit design that effectively eliminates spontaneous emission due to the Purcell effect while maintaining strong coupling to a low-Q cavity. Excellent agreement over a wide range in frequency is found between measured qubit relaxation times and the predictions of a circuit model. Using fast (nanosecond time-scale) flux biasing of the qubit, we demonstrate in-situ control of qubit lifetime over a factor of 50. We realize qubit reset with 99.9% fidelity in 120 ns.

In circuit quantum electrodynamics (cQED), engineered artificial atoms used as quantum bits (qubits) interact strongly with the electromagnetic modes of a transmission-line microwave cavity [1]. The large qubit-photon coupling affords capabilities such as coherent interactions of qubit and photon states [2], large coupling between spatially separated qubits mediated by the cavity bus [2, 3], and non-destructive joint qubit readout [4, 5]. However, this strong coupling can also cause undesirable shortening of qubit lifetime ($T_1$) due to radiative decay through the cavity [6]. This effect, first described by E. M. Purcell, describes a quantized system coupled to a resonant circuit or cavity [7]. Depending on the detuning of the system transition frequency from the cavity resonance frequency, the rate of decay of the quantum system can be strongly enhanced [7, 8] or suppressed [9-11] compared with the decay rate to the electromagnetic continuum. In cQED, qubits are generally sufficiently detuned to have suppressed decay rates, but $T_1$ can still be limited by decay through the cavity. As qubit lifetime is of paramount importance in quantum computing [12], a means of further inhibiting radiative decay is desirable.

The Purcell decay rate can be significantly reduced [6] by increasing either the cavity quality factor $Q$ or the detuning between the qubit ($\omega_q$) and cavity ($\omega_c$) frequencies, $\Delta = \omega_q - \omega_c$, but these solutions have unwelcome implications of their own. For example, reducing the cavity decay rate $\kappa = \omega_c/Q$ can diminish qubit readout fidelity [13] because fewer signal photons are collected in a qubit lifetime. A large $\kappa$ is also beneficial for resetting a qubit to its ground state by bringing it near to the cavity resonance and exploiting the Purcell-enhanced decay rate. Increasing $\Delta$ similarly has adverse effects on readout fidelity and applications that exploit large state-dependent frequency shifts [3, 14, 15]. A better solution would improve qubit $T_1$ independent of the cavity $Q$, leaving its optimization up to other experimental concerns.

In this Letter, we introduce a new design element for cQED termed the “Purcell filter”, which protects a qubit from spontaneous emission while maintaining strong coupling to a low-$Q$ cavity. We demonstrate an improvement of qubit $T_1$ by up to a factor of 50 compared to predicted values for an unfiltered device with the same $\kappa/2\pi \approx 20$ MHz. Combining the large dynamic range of almost two orders of magnitude in $T_1$ with fast flux control, we then demonstrate fast qubit reset to 99% (99.9%) fidelity in 80 ns (120 ns).

The filter works by exploiting the fact that the qubit and cavity are typically far detuned. We can therefore modify the qubit’s electromagnetic environment (e.g. the density of photon states at $\omega_q$) without, in principle, affecting the cavity $Q$ or resonant transmission. The relationship between qubit $T_1$ due to spontaneous emission and admittance $Y$ of the coupled environment is

$$T_1^{\text{Purcell}} = \frac{C_q}{\text{Re}[Y(\omega_q)]}, \quad (1)$$

where $C_q$ is the qubit capacitance [Fig. 1(a)] [16, 17]. Previous work [6] has demonstrated that Eq. (1) accurately models the observed $T_1^{\text{Purcell}}$ when all modes of the cavity are taken into account in the calculation of $Y$. As the relationship holds for any admittance, this decay rate can be controlled by adjusting $Y$ with conventional microwave engineering techniques. In particular, by manipulating $Y$ to be purely reactive (imaginary-valued) at $\omega_q$, $T_1^{\text{Purcell}}$ diverges and the Purcell decay channel is turned off. This solution decouples the choice of cavity $Q$ from the Purcell decay rate as desired, and, as we will see, has the advantage of using only conventional circuit elements placed in an experimentally convenient location.

We implement the Purcell filter with a transmission-line stub terminated in an open circuit placed outside the output capacitor $C_{\text{out}}$ [Fig. 1(a)]. The length of this stub is set such that it acts as a $\lambda/4$ impedance transformer to short out the 50 $\Omega$ environment at its resonance frequency $\omega_t$. We choose $C_{\text{out}}$ to be much larger than the input capacitor, $C_{\text{in}} \approx C_{\text{out}}/15$, to ensure that the qubit would be overwhelmingly likely to decay through $C_{\text{out}}$. The Purcell filter eliminates decay through this channel, leaving only the negligible decay rate through $C_{\text{in}}$. The combined total capacitance $C_{\text{tot}} \approx 80$ fF results in a small cavity $Q$. We use two identical stubs above and below
the major axis of the chip [Fig. 1(b)] to keep the design symmetric in an effort to suppress any undesired on-chip modes. The cavity resonates at $\omega_c/2\pi = 8.04$ GHz, the filter at $\omega_f/2\pi = 6.33$ GHz, and a flux bias line (FBL) is used to address a single transmon qubit [18] with a maximum frequency of 9.8 GHz, a charging energy $E_C/2\pi$ of 350 MHz, and a resonator coupling strength $g/2\pi$ of 270 MHz. Transmission through the cavity measured at 4.2 K was compared with our model to validate the microwave characteristics of the device [Fig. 1(c)]. There is a dip corresponding to inhibited decay through $C_{\text{out}}$ at $\omega_f$. The predicted and measured curves are also qualitatively similar, lending credence to the circuit model. This method provided a convenient validation before cooling the device to 25mK in a helium dilution refrigerator.

We measured the qubit $T_1$ as function of frequency and found it to be in excellent agreement with expectations. $T_1$ is well modeled by the sum of the Purcell rate predicted by our filtered circuit model and a non-radiative internal loss $Q_{\text{NR}} \approx 27,000$ (Fig. 2). The source of this loss is a topic of current research, though some candidates are surface two level systems [19, 20], dielectric loss of the tunnel barrier oxide [21] or corundum substrate, and non-equilibrium quasiparticles [22]. This model contains only the fit parameter $Q_{\text{NR}}$ combined with the independently measured values of $g$, $E_C$, $\omega_c$, $\omega_f$, $C_{\text{in}}$, and $C_{\text{out}}$. An improvement to $T_1$ due to the Purcell filter was found to be as much as a factor of 50 at 6.7 GHz by comparison to an unfiltered circuit model with the same $C_{\text{in}}$, $C_{\text{out}}$, and $\omega_c$, with and without the internal loss. In this case, the Purcell filter gives a $T_1$ improvement by up to a factor of $\sim 50$ (6.7 GHz).

![Circuit model of the Purcell-filtered cavity](image)

**FIG. 1.** Design, realization, and diagnostic transmission data of the Purcell filter. (a) Circuit model of the Purcell-filtered cavity design. The Purcell filter, implemented with $\lambda/4$ open-circuited transmission-line stubs, inhibits decay through $C_{\text{out}}$ near its resonance $\omega_c$. (b) Optical micrograph of the device, with inset zoom on transmon qubit. (c) Cavity transmission measured at 4.2 K and comparison to the circuit-model prediction. At $\omega_f$ (arrow) the Purcell filter shorts out the 50 $\Omega$ output environment, producing a 30 dB drop in transmission. A circuit model incorporating only the experimental parameters $C_{\text{in}}$, $C_{\text{out}}$, $\omega_c$, and $\omega_f$ shows excellent correspondence.
make repeated measurements of a coupled system, for example, requires resetting the qubit between interrogations [23]. Similarly, experiment repetition rates can be greatly enhanced when they are otherwise limited by $T_1$. Fast reset is also vital for measurement-free quantum error correction [24]. In this scheme, an error syndrome is encoded in two ancilla qubits and conditionally corrected using a three qubit gate. The ancillas, which now hold the entropy associated with the error, are then reset and reused. The Purcell filter is an ideal element with which to demonstrate reset as it allows for dramatically increased reset contrast through the use of a low-$Q$ cavity without limiting $T_1$ at the operating frequency.

The efficacy of reset in this device is readily quantified using a modified Rabi oscillation scheme, described in Fig. 3(a). Each experiment measures the degree to which the qubit is out of equilibrium after some reset time $\tau$; the protocol is insensitive to any equilibrium thermal population of the qubit. The non-equilibrium population is found to exhibit pure exponential decay over three orders of magnitude. The qubit can be reset to 99.9% in 120 ns or any other fidelity depending on $\tau$. The sequence is also performed with the qubit remaining in the operating frequency during the delay to demonstrate the large dynamic range in $T_1$ available in this system. In the case of multi-qubit devices, it is possible that this reset process would affect other qubits coupled to the same bus, but this issue could be avoided by using separate coupling and reset cavities.

The Purcell filter is an important new element for cQED which allows for the use of low-$Q$ cavities without adversely affecting $T_1$. This ability is well-suited for in-situ qubit reset, a prerequisite for measurement-free quantum error correction and other applications.

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