Quantum state characterization of a fast tunable superconducting resonator

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We demonstrate a frequency-tunable superconducting coplanar waveguide resonator, with a tuning range of half a gigahertz and a switching time of 1 ns. The resonator is made tunable by inserting a superconducting quantum interference device in the center strip of the resonator. Quantum measurements are made by probing the resonator with a superconducting qubit, allowing us to use microwave photon Fock states to benchmark the resonator performance. Using the resonator, we shuttle energy quanta between the qubit and a microscopic two-level state. The tunable resonator can, therefore, serve as a communication bus or memory element in a prototype quantum processor. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4802893]

Superconducting resonators have played an important role in quantum computation and information processing research.1,2 Resonators have been used to protect superconducting qubits from a noisy environment and to dispersively detect qubit states;3–5 to shuttle energy quanta between qubits, enabling macroscopic entanglement;6–8 and to couple different types of quantum systems, forming hybrid quantum devices.9–11 Recently, significant progress has been made in manipulating complex photon states in such resonators as well as creating macroscopic quantum entanglement.12,13 Circuits using resonators as quantum memories and as quantum communication buses have allowed the demonstration of a quantum von Neumann architecture14 and factoring the number 15 using Shor’s algorithm.15 This type of architecture, in which the qubits are complemented by memory resonators and coupled to one another via a resonator bus, was shown16 to provide sufficient performance for medium-scale quantum information processing.

Most of these experiments were performed using resonators that could only operate at a fixed resonance frequency. Significant additional flexibility can, however, be achieved using tunable resonators, giving more latitude in the operation of quantum gates, avoiding “holes” in the qubit and resonator $T_1$ spectra, and circumventing microscopic two-level states (TLSs). As observed experimentally, the frequency distribution of TLS defects is random and non-static,17 and circuit performance can be strongly affected by a nearby TLS.

The resonance frequency of superconducting resonators can be tuned by inserting a superconducting quantum interference device (SQUID) in the resonator and tuning with a magnetic field.18,19 Such a scheme has been used for signal amplification,19 for coupling spin ensembles,11 and for testing fundamental physics.20 However, single-photon control, complementary to that achieved with qubits and which is relevant to quantum information applications, has not been demonstrated using a frequency-tunable superconducting resonator.

Here, we demonstrate the fast frequency-tuning of a superconducting coplanar waveguide (CPW) resonator, with a tuning range of more than half a gigahertz. The resonator is capacitively coupled to a superconducting phase qubit, allowing single-photon experiments. We use the resonator to demonstrate quantum-coherent frequency-tuning of one- and two-photon Fock states and also use the resonator as an intermediary in the transfer of quantum states between the qubit and a spurious microscopic two-level state.

Our sample consists of a half-wavelength ($\lambda/2$) CPW microwave resonator, with a SQUID inserted in the middle of the resonator transmission line (see Fig. 1(a)); a phase qubit is capacitively coupled to one end of the resonator. A schematic circuit diagram is shown in Fig. 1(b). The SQUID can be viewed as a lumped-element inductor with a variable inductance $L_s = \Phi_0 / [4\pi L_c \cos(\pi \Phi / \Phi_0)]$, where $\Phi$ is the applied magnetic flux, $\Phi_0 = h / 2e$ is the magnetic flux quantum, and $I_c$ is the critical current of each SQUID junction. The SQUID inductance can be varied by applying an external magnetic field. For moderate detunings, the resonance frequency $f_r$ of the resonator can be well approximated by $f_r(\Phi) = f_0 / [1 + 1 / (\Psi L_c / L_r)]$, where $f_0 = (2\sqrt{LC})^{-1}$, $L$ and $C$ are the inductance and capacitance per unit length of the transmission line, and $\ell$ is the length of the transmission line.

Measurements were performed at 20 mK in a cryogen-free dilution refrigerator (Leiden CF450). The phase qubit had an energy lifetime $T_{1q} = 400$ ns and phase coherence time $T_{2q} \approx 100$ ns at its idle point of 6.39 GHz. By applying a spin echo pulse, the dephasing time could be improved to $T_{2q}^* \approx 400$ ns. We used qubit spectroscopy to characterize the qubit-resonator interaction, as described elsewhere.12 The resonance frequency of the resonator with zero applied magnetic field was around 6.9 GHz, with a qubit-resonator coupling strength of 25 MHz, consistent with the designed coupling capacitance of 2 fF. We characterized the magnetic field tuning of the resonator using the pulse sequence shown in Fig. 1(c) inset; the results are shown in Fig. 1(c). The data (dots) agree well with the calculated response (line) over the tuning range of about 670 MHz. From this measurement, the
critical current of each Josephson junction in the SQUID is estimated to be about 2.7 μA.

Using the qubit to swap single photons into and out of the resonator, we obtained the resonator’s single-photon $T_{1r}$ and $T_{2r}$ at different flux bias points (Fig. 1(d)). At small flux bias, the resonator $T_{1r}$ is approximately 2.3 μs and $T_{2r}$ is almost $T_{1r}$-limited, comparable to the performance of CPW resonators without SQUIDs. The decrease of $T_{1r}$ and $T_{2r}$ with applied magnetic field is consistent with the presence of a dissipation channel associated with the SQUID, which will be discussed elsewhere. We note that $T_{2r}$ away from zero flux can be enhanced by performing a dynamic decoupling sequence (data not shown). We mainly operated the resonator at small bias, corresponding to a tuning range of ~100 MHz, where both $T_{1r}$ and $T_{2r}$ are significantly larger than the on-resonance gate operation times.

The phase qubit couples strongly to spurious TLS at certain qubit frequencies; these TLS are thought to be atomic-size defects in the tunnel junction barrier or other dielectrics in the circuit. These TLS are most apparent when they generate Lorentzian features in the real-time swap spectroscopy of the qubit. Swap spectroscopy was performed by preparing the qubit in its $|e\rangle$ state, tuning it to a certain frequency, and monitoring the qubit $T_{1q}$ decay time as a function of the qubit frequency. This measurement gives information about the qubit’s environment, yielding, for example, the frequencies and lifetimes of strongly coupled TLS. In Fig. 2(a), we show a measurement on a sample in which a phase qubit is capacitively coupled to a fixed-frequency CPW resonator—an unlucky case where a TLS appears right near the resonance frequency of the resonator, distorting the usual Lorentzian form of the energy swapping between the qubit and the resonator. The existence of such TLS, either directly coupled to the resonator or to the qubit, causes unpredictable dispersive phase shifts and energy absorption, reducing the fidelity of quantum gates.

In Fig. 2(b), we display the results of a measurement similar to that shown in Fig. 2(a), but tuning the resonator frequency instead of the qubit frequency. We excited the resonator to the $n = 1$ Fock state using the qubit, tuned the resonator to a particular frequency, and measured its $T_{1r}$ decay time as a function of its frequency. Two-level states again appear as Lorentzian features (arrows in Fig. 2(b)). These TLS can again cause problems with gate fidelity and visibility, and having the freedom to tune the resonator away from these features can improve gate performance.

In Fig. 3, we demonstrate this additional freedom, showing three different methods for transferring photon Fock states between the qubit and the resonator. In Fig. 3(a), we tuned the qubit while keeping the resonator frequency fixed; in Fig. 3(b), we tuned the resonator while keeping the qubit fixed; and in Fig. 3(c), we tuned both the qubit and resonator to an optimal frequency. In Fig. 3(a), we kept the resonator frequency at its unbiased value, a TLS that happened to be close to this frequency generated a small modulation of the qubit-resonator swapping amplitude for the $n = 1$ Fock state, probably due to some state amplitude swapping into a defect TLS.
oscillations in Fig. 3(c) compared to Fig. 3(a) illustrates the value in choosing an optimal operating point for both the qubit and the resonator.

We further tested the device using the n = 2 Fock state, as shown in Figs. 3(d)–3(f). A clear improvement in the swap amplitude is again seen at the optimal operating point. We emphasize that in this case, to avoid the TLS interference, we only need to slightly tune the resonator from its unbiased point, preserving its T1r and T2r.

We can look in more detail at the TLS features shown in Fig. 2(b). For example, when the resonator was tuned to 6.85 GHz by biasing its SQUID at Φ/Φ0 = 0.364, the resonator was found to swap energy with a TLS with a coupling strength of 5.49 MHz, as shown in Fig. 4(a). The qubit was found to have a much weaker coupling with this particular TLS, as indicated by the arrow in Fig. 4(b). The swapping feature in this figure was almost undetectable when the resonator was detuned far from the TLS (data not shown), suggesting that this TLS is physically proximate to the resonator. Using the strong coupling to the resonator, we were able to perform quantum experiments using the TLS. We first placed the qubit in its excited state |e⟩, transferred the energy quantum into the resonator, and then swapped this excitation into the TLS by tuning the resonator to the TLS frequency. After storing the energy quantum in the TLS for a delay time, we performed a swap back to the resonator, then to the qubit for measurement. The measured qubit excited-state probability versus delay time in the TLS gives the TLS energy lifetime T1r = 380 ns (Fig. 4(c)). Using a similar sequence, we transferred the superposition state (|g⟩ + |e⟩)/√2 from the qubit to the resonator to the TLS, and then retrieved it for measurement, which yielded the TLS phase coherence time T2r = 740 ns (Fig. 4(d)). We see that T2r ≈ 2T1r, so the energy lifetime determines T2r. We emphasize that the qubit cannot directly access this TLS without the assistance of the tunable resonator, as this TLS does not couple directly to the qubit. These quantum operations, therefore, illustrate the use of the tunable resonator as a fast and switchable quantum bus.

In conclusion, we have demonstrated a rapidly tunable resonator with a frequency tuning range of more than half a gigahertz. We have performed one- and two-photon swaps between the qubit and the resonator, and swaps between the qubit and a TLS via the resonator. We believe that this kind of tunable resonator could be very useful in quantum information circuits and may also stimulate new ideas for the use of resonators in quantum computation and simulation.

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