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Tuning the field in a microwave resonator faster than the photon lifetime

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We have fabricated and characterized tunable superconducting transmission line resonators. To change the resonance frequency, we modify the boundary condition at one end of the resonator through the tunable Josephson inductance of a superconducting quantum interference device. We demonstrate a large tuning range (several hundred megahertz), high quality factors (10^4), and that we can change the frequency of a few-photon field on a time scale orders of magnitude faster than the photon lifetime of the resonator. This demonstration has implications in a variety of applications. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2929367]

Superconducting transmission line resonators have proven useful in a number of applications ranging from x-ray photon detection[1] to parametric amplification[2] to quantum information.[3–5] Very recently, there has been particular interest in tunable superconducting resonators.[6–9] These experiments have used Josephson junctions as tunable inductors, demonstrating both large tuning ranges and high quality factors (Q value). However, another critical parameter, which has not yet been measured, is the speed at which these devices can be tuned. In a number of applications in quantum information and quantum optics,[10,11] it is essential to change the frequency of photons already stored in the resonator. This means that the resonator must be tuned on a time scale much faster than its photon lifetime. Here, we demonstrate that we can tune the field in a high-Q resonator several hundred line widths on a time scale two orders of magnitude faster than the photon lifetime.

Fast tuning of the field in the resonator should enable a number of interesting applications. One is the dynamic coupling of quantum bits (qubits), which was theoretically investigated by Wallquist *et al.*[10] One advantage of using a tunable resonator in this application, compared to tunable qubits, is that the individual qubits can be kept at optimal bias points at all times. The large tuning speed should also enable the study of interesting effects in quantum optics such as the generation of nonclassical photon states[11] and the dynamical Casimir effect.[12]

Our devices consist of a quarter wavelength ($\lambda/4$) coplanar waveguide (CPW) resonator terminated to ground via one or several superconducting quantum interference devices (SQUIDs) in series [see Fig. 1(a)]. In the other end of the resonator, a small coupling capacitance is placed through which the resonator can be excited and probed by using microwave reflectometry.

A SQUID can be viewed as a lumped element inductor with the tunable inductance $L_s(\Phi)=\Phi_0/4\pi I_c|\cos(\pi\Phi/\Phi_0)|$, where Φ 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 inductance can then be varied by applying an external magnetic field. A SQUID also has a capacitance C_s and subgap resistance R_s in parallel with the inductance.

Here, we present measurements on two different devices. Device A, with one SQUID, which is tuned by an external coil and device B, with six SQUIDs in a series, which is tuned by an on-chip flux bias (see Table I). A micrograph of

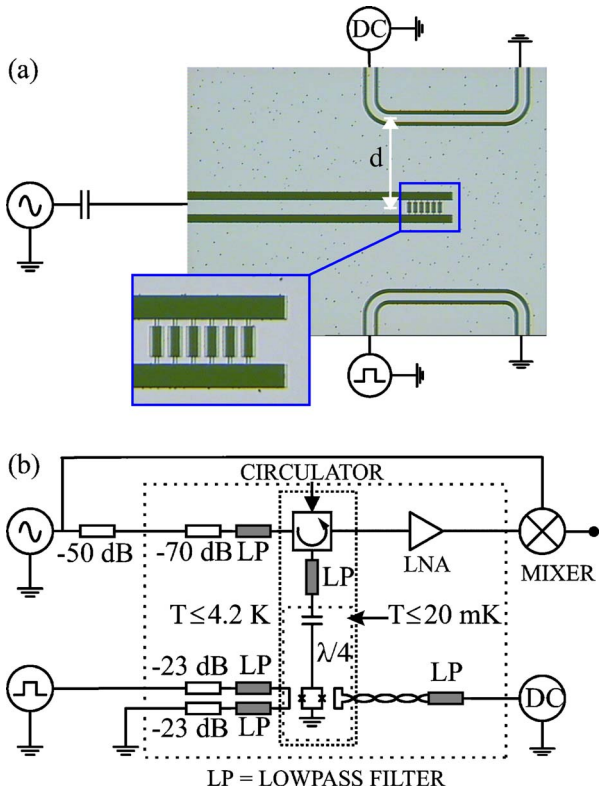

FIG. 1. (Color online) Tunable resonator and tuning speed measurement setup. (a) A schematic of a tunable $\lambda/4$ resonators with a micrograph of the terminating array of six SQUIDs. There are two on-chip flux lines; one for fast pulses and one for the DC flux bias. The area of each of the SQUID loops is 30 μm^2 and the distance d is 55 μm for the sample measured (75 μm in the picture). The devices are fabricated on a silicon substrate with a 400 nm layer of wet-grown silicon dioxide. The cavity and the Josephson junctions forming the SQUIDs are fabricated from aluminum in a single lithography step using double angle evaporation and oxidation. (b) Schematic of the measurement setup used to detect rapid changes in the resonance frequency.

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TABLE I. Parameters of the two measured devices. N is the number of SQUIDs, I_c is the critical current of the Josephson junctions, f_{max} is the zero-flux resonance frequency, Δf_{max} is the maximum detuning achieved, Q_0 is the zero field Q value, and the last column states how the flux bias was applied to the SQUID.

Sample	N	I_c (μA)	f_{max} (GHz)	Δf_{max} (MHz)	Q_0	Flux bias
A	1	1.2	4.77	744	10 000	External
B	6	2.3	4.54	580	10 000	On chip

device B is shown in Fig. 1(a). We use multiple SQUIDs to obtain larger tunability from devices that incorporate high critical-current SQUIDs. High critical currents allow for the use of higher drive powers when probing the resonator. Measurements of the devices were performed at the base temperature (below 20 mK) of a ^{3}He/^{4}He dilution cryostat. The reflection coefficient Γ was measured as a function of applied magnetic field using a vector network analyzer (VNA). From these measurements, we obtain a tunability Δf_{max} of 740 MHz for sample A and 480 MHz for sample B [see Fig. 2(a)].

The resonance frequency f_r is determined by the solution of a transcendental characteristic equation.[10] When the detuning is small, the trigonometric functions in this equation can be expanded, yielding the solution

$$f_r(\Phi) = \frac{f_0}{1 + NL_s(\Phi)/Ll}, \tag{1}$$

where $f_0 = (4\sqrt{LC}l)^{-1}$, L and C are the inductance and capacitance per unit length of the transmission line, respectively, N is the number of SQUIDs in the array (one for sample A and six for sample B), and l is the physical length of the resonator.

The total Q value is defined as $f_r/\delta f$, where δf is the full width at half maximum of the dip in the magnitude of Γ. We see that the Q value depends strongly on the detuning [see Fig. 2(b)]. Therefore, the number of detuned line widths $\Delta f/\delta f$ as a function of detuning gives a figure of merit for the devices. The maximum $\Delta f/\delta f$ is similar for the two devices and is around 250, as can be seen in Fig. 2(c). The decrease in Q value as the devices are detuned [Fig. 2(b)] can be well explained in terms of a small subgap resistance R_s of the SQUID junctions. As the devices are detuned, more power will be dissipated by the subgap resistance, lowering the Q value. The low subgap resistance is related to the high transparency of the junction barriers (670 A/cm^2 for sample A and 340 A/cm^2 for sample B). Assuming a subgap resistance R_s of 8 kΩ for sample A, which is comparable to the value measured on a reference SQUID, we can explain the decrease in Q value as well as the change in the magnitude of the resonance dip and the number of detuned line widths [see Fig. 2(c)]. For sample B, a subgap resistance of 5 kΩ is obtained, although the fit is not as good. This could be due to an observed resonance in the measurement lines, which overlapped a part of the frequency range of the device.

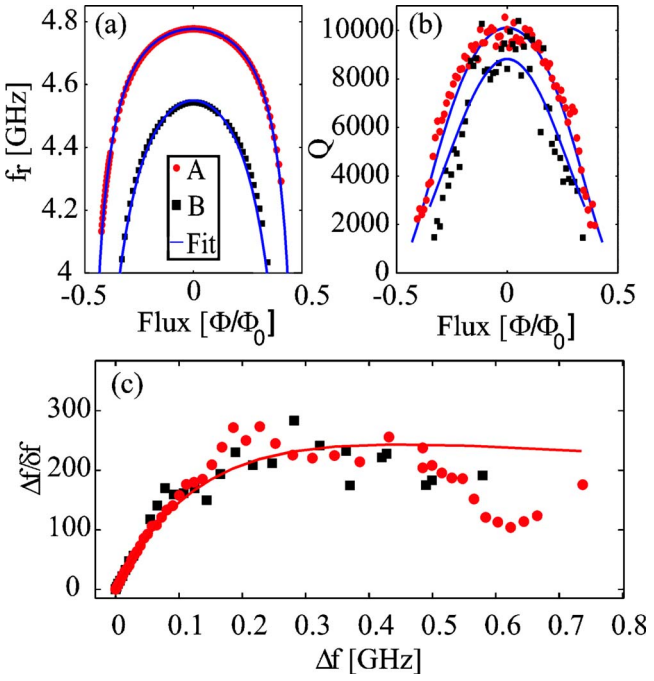

FIG. 2. (Color online) Microwave reflectometry measurements. (a) Resonance frequency for the two samples A and B. (b) Q values with a fit assuming low subgap resistance. (c) Detuning in line widths as a function of detuning. Solid line is a fit to sample A.

One of the most important aspects of the devices for physics applications is the tuning speed. A measurement of the tuning speed that relies on a change in the reflection coefficient will be limited by the ring up time of the resonator Q/ω_0. In our case, this is of the order of 300 ns. This is, however, not the same as the speed at which the resonator can be tuned.

To measure tuning speeds faster than the ring up time, we use the on-chip flux lines of device B. First, we drive the resonator on resonance until we reach equilibrium. Then, a fast flux pulse is applied that detunes the resonator. The signal leaking out from the detuned resonator is mixed with the drive signal. This produces a decaying beat signal at the difference frequency of the drive and the tuned field stored in the resonator. To obtain a good signal to noise ratio, we use, depending on drive power, between 10^5 and 10^7 averages. The observed oscillating decaying signal demonstrates that we, in fact, can tune the cavity much faster than the photon lifetime of the resonator [Fig. 3(a)].

By varying the amplitude of the flux pulse, we can map out the resonance frequency [Fig. 3(b)]. The frequencies obtained with this method agree well with the VNA measurements. We also demonstrate that, by applying positive and negative flux pulses, we can either increase or decrease the resonance frequency during the pulse.

To estimate the average photon number in the resonator in the fast detuning experiment, we can use the calculated energy stored in the field using parameters for the resonator obtained by fitting an expression for $|\Gamma|$ to the measured data. For the data shown here, around 200 photons (−123 dBm of drive power) were stored in the resonator before detuning. We also demonstrated fast tuning with drive powers of as low as −140 dBm, giving a mean photon number of 1.5.

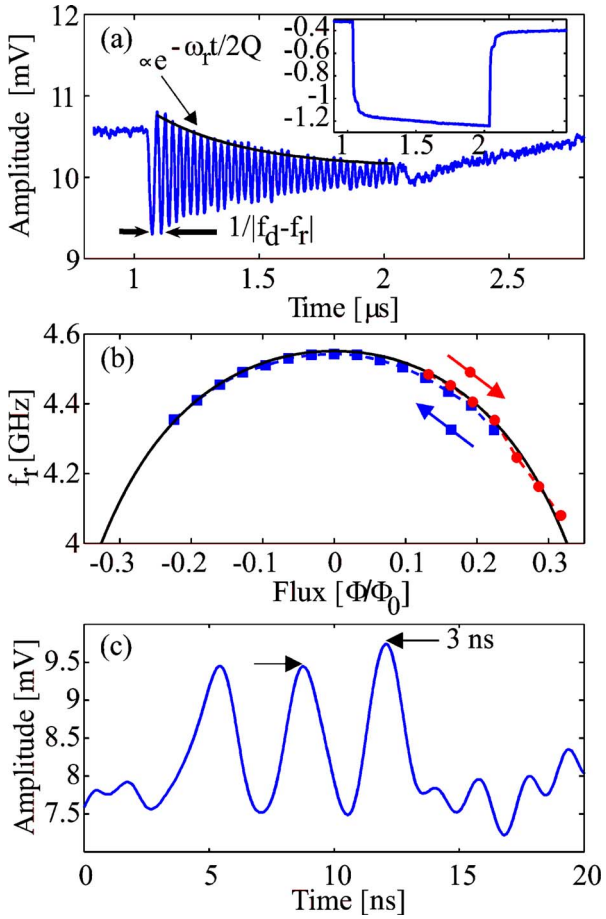

FIG. 3. (Color online) Fast tuning measurements. (a) Mixing the signal from the resonator with the drive frequency and filtering out the high frequency components as we apply a fast flux pulse to the SQUIDs. We observe a decaying, oscillating signal where the frequency of the oscillations is the difference frequency of the drive and the detuned resonance frequency. Inset: the pulse used to detune the resonance frequency. The amplitude of the pulse sets how far the resonator is detuned. (b) Resonance frequency obtained from fast pulse measurements as a function of flux pulse amplitude. We can both increase and decrease the frequency with the fast pulse meaning that we can both stretch and compress the wavelength of the field stored in the resonator. Solid line: fit to the VNA measurements. (c) Signal when a 10 ns flux pulse is applied. The detuning is 330 MHz, obtained from the period of the oscillations.

To obtain an estimate on how fast we can tune the device, we decreased the duration of the flux pulse. In Fig. 3(c), a detuning of 330 MHz for a 10 ns pulse is shown. The rise time of the flux pulse is only about 3 ns. The pulse can be decreased even further until only one oscillation is observed (not showed here), but the duration of the flux pulse is then of the same order as the rise time of the pulse.

In conclusion, we have designed and measured tunable superconducting CPW resonators. We have demonstrated a tunability of 740 MHz for a 4.8 GHz device. As a figure of merit, we see that we can detune the devices more than 250 corrected line widths. We have also demonstrated that our devices can be tuned more than two orders of magnitude faster than the photon lifetime, allowing us to change the frequency of the photon field stored inside the cavity. This can be done by several hundred megahertz in less than a few nanoseconds. We believe that the high-Q value, large tunability, and fast tunability of these devices make them candidates for dynamic coupling of qubits. It should also be an interesting system for the study of fundamental physics.

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