Coherent Operation of a Gap-tunable Flux Qubit

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We replace the Josephson junction defining a three-junction flux qubit’s properties with a tunable direct current superconducting quantum interference devices (DC-SQUID) in order to tune the qubit gap during the experiment. We observe different gaps as a function of the external magnetic pre-biasing field and the local magnetic field through the DC-SQUID controlled by high-bandwidth chip control lines. The persistent current and gap behavior correspond to numerical simulation results. We set the sensitivity of the gap on the control lines during the sample design stage. With a tuning range of several GHz on a qubit dynamics timescale, we observe coherent system dynamics at the degeneracy point.

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Superconducting flux qubits consisting of three Josephson junctions embedded in a low inductance superconducting loop are promising candidates for quantum information processing. With the standard design, the magnetic field inducing an energy difference between the ground state and the first excited state is the only parameter that is adjustable during the experiment. At the degeneracy point, it reaches its minimum value (called the gap $\Delta$), which is related to the quantum mechanical tunnel rate. However, the gap is determined at the time of production by the inherent parameters of the three Josephson junctions. One of the main problems in realizing quantum computation schemes using flux qubits is 1/f flux noise. At the degeneracy point the qubit is decoupled from low frequency flux noise, and achieves maximal coherence times of several $\mu$s rather than $ns$ at off-degeneracy point, wherefore this is the optimal operation point. Implementing a quantum processor based on flux qubits requires the operation at this optimal point at all times, especially when coupling several qubits. Recently, circuit quantum electrodynamics (QED) (quantum bus, qubus) schemes have been developed for many superconducting qubits, however standard flux qubits suffer from the fact that bringing them in resonance with such a quantum bus requires to operate them at the off-degeneracy point.

With the flux qubit we present here we aim to overcome these limitations by replacing the smallest junction of the flux qubit with a low inductance DC-SQUID loop. Varying the magnetic flux penetrating this loop is equivalent to changing the critical current of the smallest junction, thus making the gap tunable during the experiment. Using this tuning parameter we can control the coupling to a qubus by tuning into or out of the qubus frequency while operating at the optimal point. Moreover, we can implement strong transverse coupling to another qubit or to a resonator.

Our qubit is shown schematically in Fig. 1. Two identical junctions with Josephson energy $E_J$ in series with a symmetric DC-SQUID, in which each junction has a Josephson energy of $\alpha_0E_J$ are enclosed in a superconducting loop. The effective Josephson energy of the DC-SQUID is $\alpha E_J = 2\alpha_0 \cos(\pi \Phi_d/\Phi_0) E_J$, where $\Phi_d$ is the flux threading the DC-SQUID, and $\Phi_0$ is the flux quantum. The main loop is threaded by a flux $\Phi_m$. The phase drop caused by $\Phi_d$ adds up to an effective magnetic flux $\Phi_t = \Phi_m + \Phi_d/2$ threading the qubit. We operate at fluxes close to $\Phi_t = \Phi_0(n+1/2)$, where $n$ is an integer. At these points the system acts as a qubit with the Hamiltonian

$$H = \frac{\varepsilon(\Phi_t)}{2} \sigma_z + \frac{\Delta(\alpha)}{2} \sigma_x,$$

where $\varepsilon = 2I_p(\Phi_t - \Phi_0(n+1/2))$ is energy difference between the two different classical persistent current states induced by the external magnetic field, and $\Delta(\alpha) \equiv \Delta(2\alpha_0 \cos(\pi \Phi_d/\Phi_0))$ is the tunnel element between these two states, and $\sigma_x$ and $\sigma_z$ are Pauli matrices.

There is intrinsic crosstalk between the DC-SQUID flux and the effective qubit flux, unrelated to an inductive crosstalk of the control lines to either loops, since $\Phi_t = \Phi_m + \Phi_d/2$. This strong crosstalk will shift the operation point of the qubit, thus causing strong dephasing and transitions to higher levels. F. G. Paauw et al. utilize a gradiometric double loop design to solve this...
problem. With N fluxoids (N is an odd integer) trapped in the superconducting loop of the gradiometer the qubit is pre-biased close to its degeneracy point. They realized the in situ tunability of a gap. However, a short relaxation time prevented further experiments.

In our design, we place two control lines, 1 and 2 (Fig. 1), adjacent to the qubit structure. The fluxes in the qubit loops are related to the control currents by the mutual inductances to the respective lines. The mutual inductances of control line 1 to the DC-SQUID loop and main loop are 85 fH and 64 fH, and those of control line 2 are 1 fH and 84 fH respectively. We carry out our experiment as follows: first we pre-bias the effective qubit flux $\Phi_t$ close to the operating point $(n+1/2)\Phi_0$ by using the external magnetic coil located in the Dewar. This operation is slow, since the solenoid has a settling time on the order of minutes. Applying currents to the control lines tunes $\Phi_t$ and $\Phi_d$ in situ away from their pre-biased values. The coupling to the effective qubit loop induced by control line 1 can be compensated by applying the corresponding current to control line 2, thus giving full control over the two-dimensional parameter space.

In Fig. 2(a-c), we show the change in the gap $\Delta$ as a function of the pulse voltage level of control line 1 while using control line 2 to scan the parameter effective magnetic flux $\Phi_t$. In this measurement, $\Phi_t$ is pre-biased to an operation point near $3/2\Phi_0$ (See below for details on the choice of the operation point). Because the mutual inductance of the control line 2 to the DC-SQUID loop is much smaller than that to the main loop, we can neglect the influence of control line 2 on $\Phi_d$ and assume that the gap is constant during each scan. Therefore, the spectra obtained here are similar to that of a traditional 3JJ flux qubit. Each curve can fit to the dispersion relation of the qubit Hamiltonian in Eq. 1, given by

$$\Delta E = \sqrt{\varepsilon (\Phi_t)^2 + \Delta(\alpha)^2},$$

(2)

FIG. 2. Spectra with different gaps: the gaps $\Delta$ and persistent currents $I_p$ are (3.26 GHz, 166.8 nA)(a), (5.05 GHz, 155.3 nA)(b) and (6.84 GHz, 144.6 nA)(c) by setting shift pulse voltage level of control line 1 at 0.0, 1.2 and 2 V respectively. $\Delta$ and $I_p$ were obtained by fitting the spectra to Eq. 2 (blue dashed line)

so we obtain the gap $\Delta$ and the persistent currents $I_p$ by fitting.

The bandwidth of our control lines is 20 GHz. This imposes no relevant limit to the proposed schemes on the speed with which we can tune the flux of the loops in situ. On the other hand, because we now intend to tune the qubit adiabatically, the tuning frequency should be much smaller than the energy level space between the ground state and the first excited state. Hence, we limited the pulse rise-and-fall times of the pulse generators in this measurement to 1.6 ns. This value is also suitable for demonstrating selective qubit coupling to a quantum bus by tuning into resonance.

We extract the persistent currents and the gaps from the spectra, and plot them in Fig. 3 (circles) as a function of $\alpha$ values (three of the original spectra are shown in Fig. 2). The lines are fitting results of the numerical diagonalization of the full discretized Hamiltonian in a finite difference scheme. The charging energy $E_c=5.05$ GHz, the Josephson energy $E_J=139$ GHz and $2\alpha_0=0.95$ in the numerical calculation are obtained by fitting to the experimental data. The charging energy $E_c$ compares well with the values obtained earlier for similar production parameters.

It should be pointed out that the sensitivity of the gap on the DC-SQUID loop frustration $|d\Delta/d\Phi_d|=|(d\Delta/d\alpha)\cdot(d\alpha/d\Phi_d)|$ depends on the pre-biasing point. When $\Phi_t$ is pre-biased to $(n+1/2)\Phi_0$ and no shift pulse is added to the qubit, $\Phi_d$ is only determined by the external mag-
netic coil and is equal to \((n + 1/2)\gamma \Phi_0\), where the factor \(\gamma = S_d/S_l = 0.138\) is the ratio of the DC-SQUID loop area \(S_d\) to the effective qubit loop size \(S_l\) which is \(S_l = S_m + 1/2S_d\). Since \(\frac{d\omega}{d\Phi} = \frac{2\pi\gamma}{\Phi_0} \sin(\pi(n + 1/2)\gamma)\), and \(d\Delta/d\omega\) obtained from Fig. 3(b), we can calculate the \(|d\Delta/d\Phi_d|\) value at each pre-biasing point. At the working points selected in this measurement, \(|d\Delta/d\Phi_d|\) is equal to 3.96 GHz/\(\Phi_0\) (at \(\Phi_d = 1/2\gamma \Phi_0\)) and 56.5 GHz/\(\Phi_0\) (at \(\Phi_d = 3/2\gamma \Phi_0\)) (these two points are shown by black solid circles in Fig. 3). This calculation shows that the sensitivity at \(\Phi_d = 3/2\gamma \Phi_0\) is more than ten times larger than at \(\Phi_d = 1/2\gamma \Phi_0\). So, we choose the bias point \(\Phi_t = 3/2\Phi_0\) as the working point for experiments on controlling the gap (open circles in Fig. 3). We can control the sensitivity at a given qubit gap during the design of the sample by adjusting \(a_0\), \(\gamma\) and choosing the pre-bias point appropriately to obtain a larger sensitivity. However, the greater sensitivity also increases the effect of the flux noise. Therefore, future applications of these kind of gap-tunable flux qubits require to balance these two conflicting factors.

Rabi oscillations between the ground state and the first excited state are an elementary demonstration of a single qubit coherent operation. In Fig. 4(a), we show Rabi oscillations obtained at the degeneracy point. We set the voltage level of the two control lines to the degeneracy point appropriately to obtain a larger sensitivity. However, the greater sensitivity also increases the effect of the flux noise. Therefore, future applications of these kind of gap-tunable flux qubits require to balance these two conflicting factors.

We varied the amplitude of the microwave, and verified the linear dependence of the Rabi frequency on the microwave amplitude as shown in Fig. 4(b), which is a signature of the Rabi process.

In summary, we designed and fabricated an improved flux qubit, whose gap can be tuned \textit{in situ} by two high bandwidth control lines. We also demonstrated coherent Rabi oscillations at the degeneracy point. This gap tunable flux qubit is a promising candidate for the implementation of scalable quantum computation.

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