Picosecond On-Chip Qubit Control Circuitry

Thomas A. Ohki, Michael Wulf, and Mark F. Bocko

***Abstract*—Fast on-chip control of superconducting qubits has engaged complex and power consuming RSFQ circuits that currently pose more of an experimental burden than an asset. Measurements of quantum coherent oscillations of qubits require dilution refrigerator temperatures. The motivation of this design is to minimize the necessary bias leads and power dissipation for an SFQ based control circuit. Elimination of redundant circuit elements by innovative use of fundamental elements allows small-scale control circuitry.**

***Index Terms*—RSFQ circuits, superconducting qubits.**

I. Introduction

THE ABILITY to use integrated circuit components monolithically on a single chip to interact with qubits will provide the necessary groundwork for a solid-state quantum computer. Several schemes for constructing a super-conducting quantum computer [1] on an integrated circuit have been proposed, and several superconducting qubits have been probed for coherence properties that can be used in a scheme for quantum computation.

Any integrated circuit implementation of a quantum computer will require supporting classical electronics for qubit manipulation. A particularly convenient approach for performing such tasks is with rapid single flux quantum (RSFQ) superconducting digital circuitry [2]. RSFQ utilizes the natural quantization of magnetic flux in superconductors as data bits that can be shuttled between circuit elements and stored in order to perform logical functions. Since RSFQ is a magnetic flux based logic family a sound choice for a qubit would be one that is easily manipulated with magnetic field, such as the rf-SQUID [3], the persistent-current qubit [4] and the dc-SQUID phase qubit [5]. Traditionally, RSFQ integrated circuits have been fabricated in Niobium that can be cooled with liquid Helium to the superconducting state.

We have designed and tested an SFQ circuit that will be used in an experiment to measure the quantum coherent oscillation of the phase in a superconducting hysteretic dc-SQUID phase qubit. Rabi oscillations have been shown for this qubit with 150 ns coherence times [5]. Energy level quantization experiments using SFQ control circuit have been demonstrated [6].

The concept is exceptionally simple. An unbiased SFQ/DC converter toggles between two states that differ by $\pm$ one flux quantum in an inductive loop, when successive SFQ pulses are applied to its input. This magnetic field is very weakly coupled to a qubit to produce small, fast, changes in the qubit bias. A room temperature delay line controls the duration of the magnetic field ON time. The circuit is able to rapidly change a two-state magnetic field qubit bias with a (simulated) 15 ps rise time (10%–90%) and a duration as short as 200 ps. High frequency attenuation and dispersion due to the frequency dependant impedances of coaxial lines and inadequate high frequency impedance matching onto the microchip are known experimental roadblocks. This design aims to circumvent these issues. The circuit acts like an on-chip pulse shaper for applications that involve fast square pulses in order to modulate a qubit potential or to address gates.

II. RSFQ Design

The chips were fabricated by Hypres, Inc. using their 100-A/cm^2 process [7]. The Josephson junctions are $Nb/AlO_x/Nb$ trilayers, Nb leads and inductors and Palladium resistors of 2 Ω/sq.. The β_c of our design is $\sim$1.2, which sets the lower bound of operational speed at about the SFQ pulse width, about 20 ps. The peak power dissipated per junction is $2I_c^2R \sim 20$ nW. The average power is much less, being determined by the product of the SFQ pulsewidth and the repetition rate. The circuit only has 13 junctions. Assuming that an experiment is repeated at the high rate of once every microsecond, these numbers give us a total average on-chip power dissipation of $\sim$5 pW. In order to minimize the power dissipated on chip there are no bias resistors on the chip. The only power consuming elements remaining are the junctions in the voltage state and their shunt resistors that absorb transient signals. Bias resistors are normally used to divide current on chip. Since we are concerned with heating issues [8] we choose not to implement them in this design. The circuit is comprised of a DC/SFQ converter and an SFQ/DC converter [9]. The simplicity of the design allows for a smaller circuit area that tends to reduce the impact of resistor and junction parameter scatter that is a byproduct of fabrication (Fig. 1). Also, it allows for fewer bias leads and greater flexibility for wide margins of operational parameters. Fig. 2 (top) shows the circuit layout. The coupling of this device to the dc-SQUID qubit is achieved inductively and is illustrated in Fig. 2 (bot). The top loop in Fig. 2 (bot) is able to store 0 or 1 flux quanta.

We have coupled the dc-SQUID with a mutual inductance of $\sim$3.2 pH and a coupling constant $k \sim 0.25$. A reduced mutual inductance will allow smaller perturbations to the qubit potential. This may be beneficial to realize adiabatic control; furthermore it improves the qubit isolation from the control circuit shunt resistors. The flux storage loop has a self-inductance of 16.56 pH, whereas the self-inductance of the dc-SQUID is

Manuscript received October 5, 2004. This work was supported in part by AFOSR Grant F49620-01-1-0457 funded under the Department of Defense University Research Initiative on Nanotechnology (DURINT) Program, by ARDA, and ARO grant DAAD19-02-1-0181.

The authors are with the Superconducting Digital Electronics laboratory, University of Rochester, Rochester, NY 14627 USA (e-mail: tohki@pas.rochester.edu).

Digital Object Identifier 10.1109/TASC.2005.850076

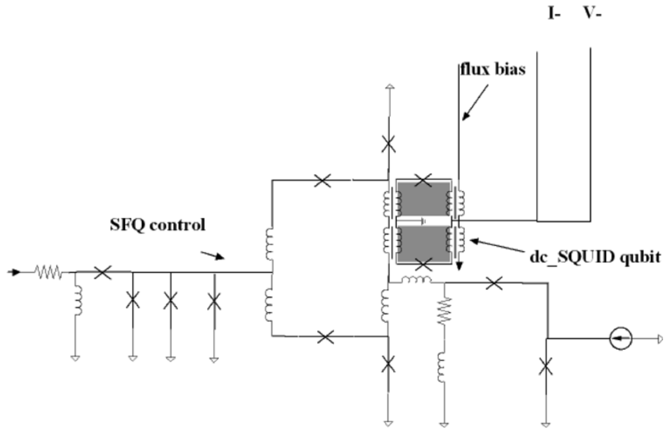

Fig. 1. Schematic of the control circuit with the shaded element being the qubit.

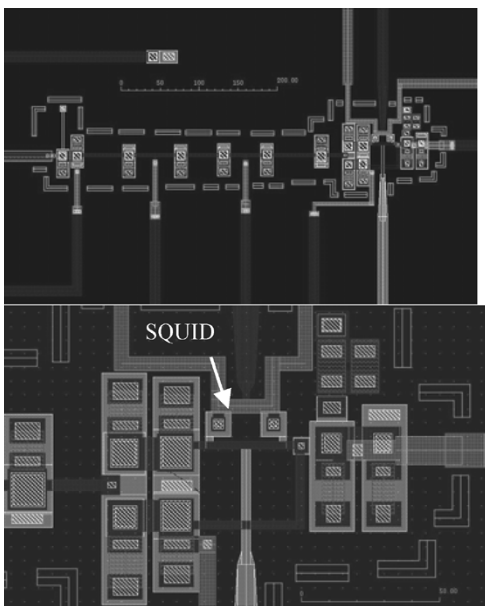

Fig. 2. Top figure is the layout of the control circuitry. The lower figure shows the dc-SQUID qubit coupled to the storage loop.

~10 pH. The operational principle is as follows: A square current pulse is sent into the DC/SFQ input resulting in an SFQ pulse for each rising edge. Each SFQ pulse then loads or unloads the flux storage loop so that either 1 or 0 flux quanta are in the loop. This corresponds to a difference in the loop of about 120 μA of current. We use the constant magnetic field to then alter the qubit potential.

III. DC-SQUID Qubit

The dc-SQUID phase qubit has shown promising results. The dynamics of the dc SQUID can be approximated to be the same as a single Josephson junction assuming $\beta_{\mathrm{L}} \ll 1$. Our SQUID has a β_{L} of ~0.1. Subsequently, the energy levels in the tilted sinusoidal potential are predicted to be [10]

$$\mathrm{E_n} \cong \hbar\omega_p \left[\left(n + \frac{1}{2} \right) - \frac{\hbar\omega_p}{432\Delta U}(11 + 30n + 30n^2) \right]. \quad (1)$$

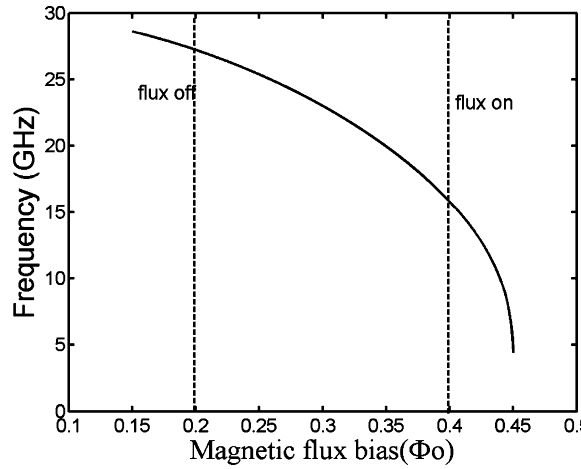

Fig. 3. Flux states coupled by the control circuitry are shown by the dotted lines. There is a dc flux bias of $0.2\Phi_{\mathrm{o}}$. The on-off states differ by $0.2\Phi_{\mathrm{o}}$. The change in resonance frequency is ~12 GHz. We can bring the qubit nonadiabatically into resonance with a cw microwave field and then remove it to a far off resonance state.

Where $\omega_{\mathrm{p}}(\Phi_{\mathrm{o}})$ is the reduced plasma frequency, $\Delta\mathrm{U}(\Phi_{\mathrm{o}})$ is the barrier height and $\mathrm{n} = 0, 1, 2\ldots$ is the energy level number. The SQUID critical current is $\mathrm{I_o} = 5\ \mu\mathrm{A}$ where $\mathrm{I_c}$ is defined by the equation [11]

$$\mathrm{I}_c \cong 2I_o \left| \cos\left(\pi \frac{\Phi_e}{\Phi_o} \right) \right|. \quad (2)$$

The $\mathrm{E_0}$ to $\mathrm{E_1}$ transition can be expressed as a function of the magnetic field bias on the SQUID.

We have performed spectroscopy of the current biased single junction and the dc-SQUID and shown results that are consistent with energy level quantization [12]. We accomplish this by ramping current through the SQUID and then measuring the point at which it switches from the zero-voltage state to the finite-voltage state [13]. This process is done while applying a cw microwave field at all relevant frequencies.

IV. Circuit Operation

A. Qubit Control

The control circuitry is able to generate two flux states which are used to bias the qubit. We are also able to flux bias the SQUID with a dc field that inductively couples on chip. We perform the on chip bias since we use a ground plane on the chip. In Fig. 3, a 0.2 Φ_{o} dc bias was set and the flux bias from the control circuitry is toggled to be on or off. For the designed coupling the on-off states differ by $0.2\Phi_{\mathrm{o}}$. The flux states perturb the potential and thus the energy level separations such that the qubit can be brought in and out of resonance with the a ~16 Ghz cw microwave field. When on resonance, the population coherently oscillates between the ground and first excited states. If the time that the qubit is on resonance exceeds the coherence time of the coherent oscillations then spectroscopy is performed. In order to resolve oscillations in population, the transition must be resonantly driven for smaller time scales than the characteristic coherence time but more importantly shorter than the period of coherent oscillations. For this qubit, at the specified power, this frequency was on the order of 7 MHz. So the pulsed flux bias

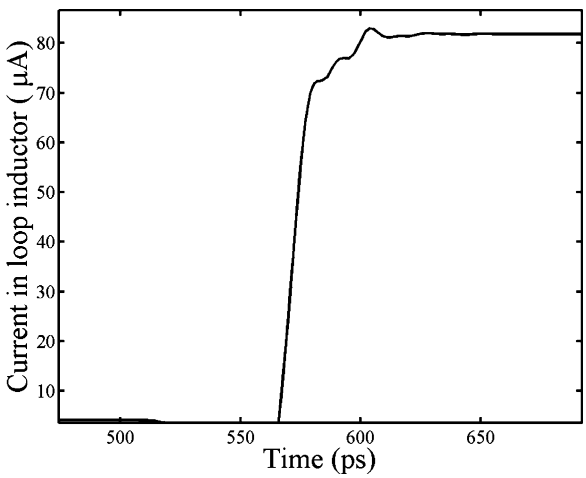

Fig. 4. Jspice3 simulation of the ∼50 ps rise time of the current in the loop inductor due to the flux pulse.

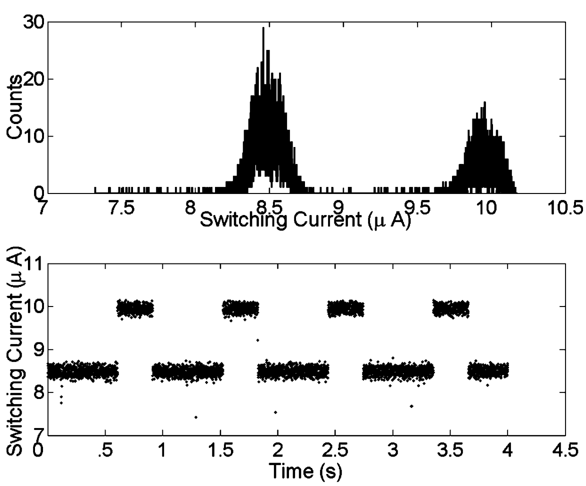

Fig. 5. Flux state is switched on and off with an input pulse sequence at ∼1 Hz. The switching current of the dc-SQUID is measured at 4 K at a 1 kHz data rate. (top) Figure shows the counts versus bias current. The flux bias suppresses the Ic by $\sim 1.5\ \mu$A which in units flux is equivalent to 0.2Φo. (bot) Switching current versus time.

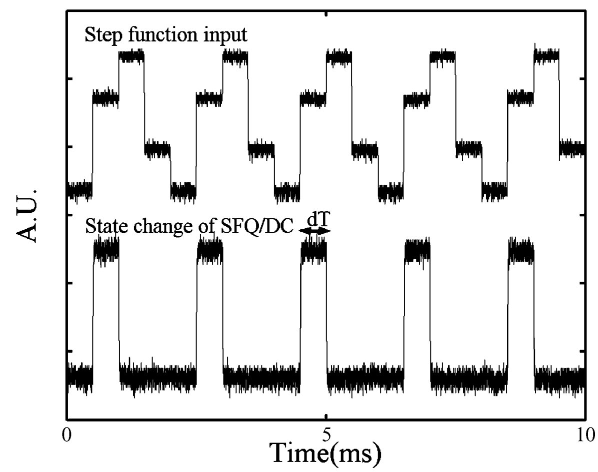

Fig. 6. Double pulsing the DC/SFQ creates two SFQ pulses that load and unload the flux bias loop. The top curve is the input step function. The bottom is the output of a SFQ/DC converter. The state change at the output shows that the flux loop has either 0 or 1 Φ_o.

must have an effective pulsewidth preferably $\ll 2\nu \sim 14$ MHz or 70 ns. A Jspice simulation shows the rise time of the flux change to be about 50 ps as illustrated in Fig. 4 and the length of the pulse can be as short as 200 ps.

V. Experimental Results

We have been able to measure the impact of toggling the flux state by making a switching current measurement while pulsing the input of the DC/SFQ. The measurement is performed using the procedure described in [8]. As shown in Fig. 5, The two switching currents differ by $\sim 1.5\ \mu$A which in units of flux is equivalent to 0.2 Φ_o that is threading the SQUID loop.

A. Pulsing the Input

In order to get short pulse lengths a few things are necessary. First, the input pulse must have a fast rise time. This is necessary due to the dispersion that is caused by room temperature and cryogenic transmission lines. If the first pulse is subject to dispersion the second pulse will be immeasurably altered. Thus the critical timing between each successive SFQ pulse created at the threshold point of the rising edge is an experimental unknown.

The experimental setup implements a fast tunnel diode with a rise time of 20 ps. The turn-off time of the diode is as long $\sim 1\ \mu$s. The solution to this problem is to take a single diode edge, split the signal, delay one of the lines and recombine the pulse to get a staircase type function. We are unable to measure the SFQ/DC output at high speeds due to our current sample holder. To show proof of principle, a low speed (2 kHz) test of this double pulse technique was done at 4 K as shown in Fig. 6. By pulsing the DC/SFQ input with a step function a SFQ pulse can be created at each rising edge. This allows us to set the delay, dT, between the steps to create two very closely spaced SFQ pulses.

The timing of this experiment is as follows: Initially the dc-SQUID qubit is dc flux biased to suppress the Ic to where the control circuitry can change the energy level separation to be on resonance with the cw microwave. Then the input staircase pulse will flop the state of the storage loop thus allowing a controlled pumping of the first excited state. Each experiment begins when the flux state of the control circuitry is toggled then held for many different delay times, dT. Shortly after the flux is turned off and the qubit is out of resonance a quick measurement of the escape probability is made. The read-out of the qubit state will be preformed using the procedure described in [5]. The qubit is biased just below its critical current with a fast current pulse and then the bias is reduced and held so as to make a “slower” measurement of the junction escape voltage (Fig. 7).

It is necessary to leave the output junction unbiased so that ringing in the current does not impact the stable flux bias. This creates the problem that the flux state is not known during the experiment. In order to make sure the bias condition was properly changed we must check for errors at the end of the experiment.

Error checking can be done, when necessary, by pulsing the output junction and measuring the resulting voltage state. This

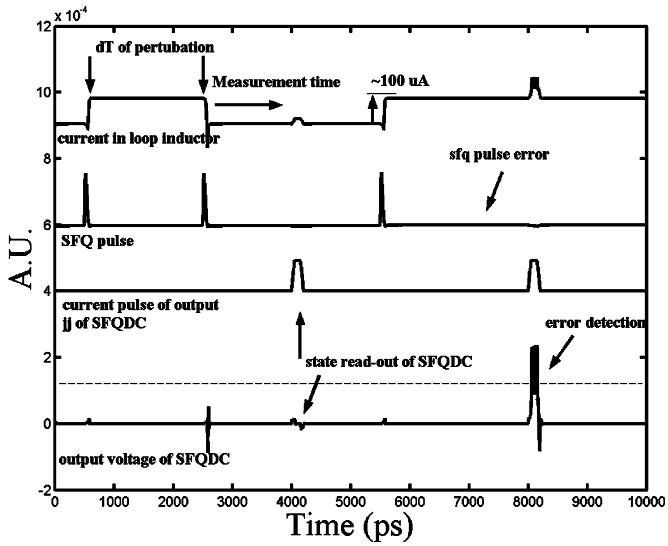

Fig. 7. Experiment begins when the flux state of the control circuitry is toggled for many different dT. Shortly after the flux is turned off and the qubit is out of resonance a quick measurement of the escape probability is made. Pulsing the output junction of the SFQ/DC and measuring the digital state can accomplish subsequent error checking.

can be done slowly in comparison to the experiment's total time. When bias conditions of the circuit are optimized, infrequent readout of the state is necessary.

VI. Conclusion

The on-chip circuitry designed and tested is able to perform picosecond control functions on qubits. This design can be implemented for flux qubits, as well as phase qubits in order to achieve gate operations on qubits. The benefits of the design includes the low power dissipation, its simplicity and it's robust operation due to large parameter margins. We are able to change the energy level separation of a phase-based dc-SQUID qubit using fast on-chip control circuitry. The 50 ps rise time and 200 ps minimum pulsewidth makes this circuit capable of performing experiments to observe coherent oscillation in a phase qubit.

References

[1] T. P. Spiller, *Fortschr. Phys.*, vol. 48, p. 1075, 2000.
[2] M. J. Feldman and M. F. Bocko, *Physica C*, vol. 350, p. 171, 2000.
[3] M. F. Bocko, A. M. Herr, and M. J. Feldman, " Prospects for quantum coherent computation using superconducting electronics," *IEEE Trans. Appl. Supercond*, vol. 7, no. 2, p. 3638, Jun. 1997.
[4] T. P. Orlando *et al.*, *Phys. Rev. B*, vol. 60, p. 15 398, 1999.
[5] C. Cosmelli, P. Carelli, M. G. Castellano, F. Chiarello, G. D. Palazzi, R. Leoni, and G. Torrioli, *Supercond. Sci. Technol.*, vol. 16, p. 1337, 2003.
[6] Y. Yamanashi, M. Ito, A. Tagamai, and N. Yoshikawa, "Observation of quantized energy levels in a Josephson junction using SFQ circuits," in *Proc. Applied Superconductivity Conf.*, Jacksonville, FL, Oct. 2004, pp. 1–4.
[7] *Hypres Niobium Process Flow and Design Rules*, Hypres, Inc., Elmsford, NY.
[8] T. A. Ohki, M. Wulf, J. P. Steinman, M. J. Feldman, and M. F. Bocko, "Thermometry using thermal activation of Josephson junctions at MilliKelvin temperatures," *Proc. Applied Superconductivity Conf.*, pp. 1–4, Oct. 2004.
[9] K. K. Likharev and V. K. Semenov, "RSFQ logic/memory family: a new Josephson-junction technology for sub-terahertz-clock-frequency digital systems," *IEEE Trans. Appl. Supercond.*, vol. 1, no. 1, pp. 3–28, Mar. 1991.
[10] H. Kleinert and I. Mustapic, *Int. J. Mod. Phys. A*, vol. 11, p. 4383, 1996.
[11] J. M. Martinis, M. H. Devoret, and J. Clarke, *Phys. Rev. B*, vol. 35, p. 4682, 1987.
[12] M. Wulf, T. A. Ohki, X. Zhou, and M. Feldman, "Dressed states of Josephson phase qubit coupled to an *LC* circuit," *Proc. Applied Superconductivity Conf.*, pp. 1–4, Oct. 2004.