Low-noise computer-controlled current source for quantum coherence experiments

S. Linzen, T. L. Robertson, T. Hime, B. L. T. Plourde, P. A. Reichardt, and John Clarke[a]

Department of Physics, University of California, Berkeley, California 94720-7300

We describe a dual current source designed to provide static flux biases for a superconducting qubit and for the Superconducting QUantum Interference Device (SQUID) which measures the qubit state. The source combines digitally programmable potentiometers with a stabilized voltage source. Each channel has a maximum output of ± 1 mA, and can be adjusted with an accuracy of about ± 1 nA. Both current supplies are fully computer controlled and designed not to inject digital noise into the quantum bit and SQUID during manipulation and measurement of the flux. For a 275 μA setting, the measured noise current is 2.6 parts per million (ppm) rms, in a bandwidth of 0.0017–10 Hz, from which we estimate dephasing times of hundreds of nanoseconds in the particular case of our own qubit design. By resetting the current every 10 min, we are able to reduce the drift to no more than 5 ppm at a current of 750 μA over a period of 3 days. The current source has been implemented without thermal regulation inside a radiofrequency-shielding room, and is used routinely in our quantum coherence experiments. © *2004 American Institute of Physics.*. [DOI: 10.1063/1.1771499]

I. INTRODUCTION

There is worldwide experimental and theoretical research in the field of quantum coherence involving a variety of quantum bits (qubits), the basic elements of a possible future quantum computer.[1] A promising solid state variant is the superconducting flux qubit,[2,3] which can be read out with a dc Superconducting QUantum Interference Device (SQUID).[4] In our own device[5] the magnetic fluxes in the SQUID and qubit are applied by inductive coupling to static currents in two lines fabricated on-chip. The requirements for these bias currents are as follows:

(i)   A current setting with a resolution of ± 1 nA and a bipolar range of ± 1 mA is required for our qubit/SQUID design.[5] These currents enable us to achieve a resolution of about 2.5 $\mu\Phi_0$, corresponding to a change in qubit resonant frequency of ~ 5 MHz, in qubit spectroscopy over a range of about ± 2.5 Φ_0. Here, $\Phi_0 \equiv h/2e$ is the flux quantum. The maximum required current cannot be decreased significantly by increasing the mutual inductances to the qubit, as these inductances must be small to limit decoherence produced by the impedance of the flux bias circuitry.[6]

(ii)   An experiment may involve setting the two fluxes thousands of times over tens of hours. Current stability is required for periods of 10 min or more, the time to acquire a complete spectrum. A reasonable criterion might be that the drift in qubit frequency should be no more than 10 MHz, a figure less than the width of our resonance lines. During this time, no adjustments to the system should be made so that data within a single

spectrum are entirely consistent. Furthermore, the current noise of the supply should not be the limiting source of decoherence in the experiment.

(iii)   The current supply is required to maintain current stability over the course of several days, as repeated measurements of the spectrum under varying conditions may constitute a single experiment. However, a recalibration procedure, which should not take more than a minute, may be implemented between spectra.

(iv)   Full computer control of the current supply is required throughout the acquisition of data for a spectroscopic measurement. Typically, data are averaged over an ensemble of 2000–5000 qubit readout processes for each flux step, and 100–200 values of the flux are required to produce a spectrum.

(v)   The current supplies must be able to operate inside a radiofrequency shielded room and be well isolated from digital noise sources such as computers and monitors and from 60 Hz power line interference. The shielded room surrounds a dilution refrigerator that cools the qubit and SQUID to millikelvin temperatures, and also contains the electronics required to read out the flux state of the qubit.

In this article, we describe a dual current supply that meets these requirements. Commercially available current supplies appear not to be adequate.

II. DESIGN

Our current supply combines digitally programmable potentiometers with a stable voltage reference. Digitally controlled potentiometers, for which the digital signal—including the clock—can be turned off after they have been adjusted, are commercially available (for example, Analog

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[a]Author to whom correspondence should be addressed; electronic mail: jclarke@physics.berkeley.edu
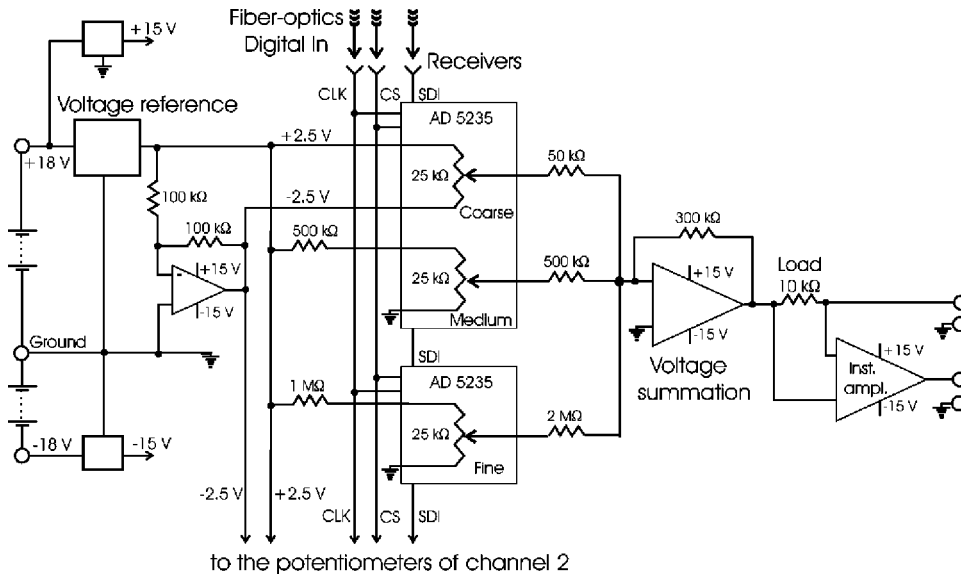
FIG. 1. Schematic of one current source; second source is identical. The second potentiometer on the AD5235 chip containing the fine control is unused in our current design.

Devices, Norwood, MA). This feature enables us to set the current to a target value, and subsequently make qubit manipulations and measurements with no interference from digital signals.

The circuit, shown in Fig. 1, is fabricated on a 90×170 mm^2 double-sided circuit board with a minimum linewidth of 0.25 mm. The board is supplied by ± 18 V NiCd batteries which share a common ground with the shielded room. The voltage reference (AD 584, bandgap type) is configured for an output voltage of $+2.5$ V, the maximum allowed voltage for the potentiometers. A low-noise operational amplifier (Burr-Brown OPA 627) is used as an inverter to provide the negative voltage necessary for bipolar current output. These $+2.5$ V sources, which are stable for currents up to 10 mA, are designed to have a temperature coefficient of better than 15 ppm/K and a peak-to-peak noise less than 50μV in the bandwidth 0.1–10 Hz. The three 25 kΩ potentiometers, each connected to a different series resistor, define the coarse, medium and fine ranges of the current source. The three currents are summed by an operational amplifier (OPA 627) with a gain of 6 for the coarse range. Thus, the maximum voltage at the amplifier output is ± 15 V, producing a current of ± 1.5 mA through a 10 kΩ load resistor. A unity-gain instrumentation amplifier (AD 620), which measures the voltage across the load to sense the output current, can monitor a maximum voltage of 10 V, thus limiting the usable current range to ± 1 mA. The output of the battery powered instrumentation amplifier is fed through the wall of the shielded room and is measured with a high impedance voltmeter (HP 34401A). This instrument has an IEEE 488.2 connection to the data acquisition computer with an isolated ground; however, when we used a common ground there was no discernable difference in performance.

The maximum current outputs of the coarse, medium and fine potentiometers are 1.5 mA, 7.1 μA, and 0.94 μA, respectively. Since the potentiometers (AD 5235) have resistor ladders with 1024 values, the corresponding step sizes are 1.46 μA, 6.9 nA, and 0.92 nA, respectively. We set the potentiometers with a digital sequence which is sent over a

serial peripheral interface (SPI) compatible bus implemented through an optical link. The three signals necessary—clock (CLK), data (SDI), and chip select (CS)—are sent individually from the digital outputs of the controlling computer to LED transmitters (Agilent HFBR-1412T) which convert the electrical signals to optical signals. The light travels across three 62.5/125 μm optical fibers, each 10 m in length, to a bank of photodiode receivers (HFBR-2412T) which reconvert it to electrical signals on the current supply board. The serial data signals are distributed in a daisy-chain configuration of the three potentiometers. The potentiometers are set with the nonstandard logic levels of 0 and 2.5 V, which we generate with voltage dividers on the board.

We designed the current source without a feedback loop. Such a loop might well induce additional $1/f$ noise, and is not required for our purposes since the drift over the time of a spectral measurement, typically 10 min, is insignificant. We compensate for drifts over longer periods by means of software control, as described below.

We control the two currents using LabVIEW® software running on a desktop computer, which programs the potentiometers through the digital output of a National Instruments PCI-6052E data acquisition card over the SPI-compatible bus described above. An instruction in our configuration consists of a series of 24 bit data-words, each addressing a different potentiometer and containing a "write data to digital potentiometer" command paired with an appropriate resistance setting. Since the integral nonlinearity of the AD5235 can be a significant fraction of a step in the least significant bit, and because of nonlinearities introduced by the load connected to the wipers of the digital potentiometers, setting the outputs by dead reckoning gives inaccurate outputs. Rather, to determine the appropriate potentiometer settings for the desired current quickly and accurately, our software retrieves settings from a look-up table containing measured currents from a calibration procedure, choosing the closest available setting for the coarse, medium and fine controls in sequence. This table contains entries for every possible setting of each potentiometer; thus, for a channel served by three potentiometers the table contains 3072 entries.
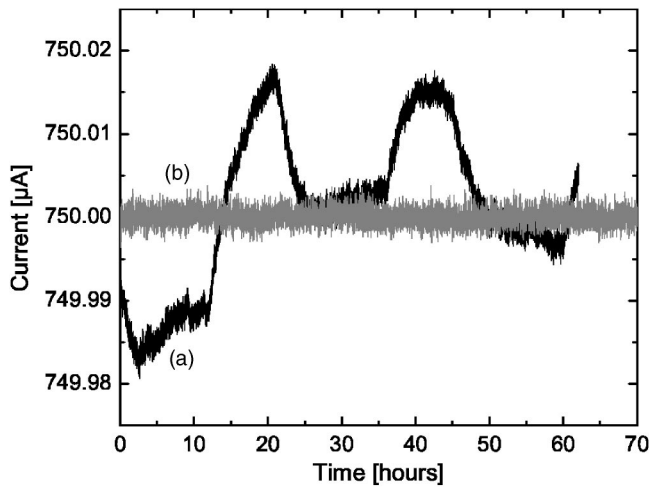
FIG. 2. Current stability over 70 h (a) without control and (b) controlled by Labᴠɪᴇᴡ® program. The sampling rate was 0.5 Hz, corresponding to a measurement bandwidth of 0.25 Hz.

FIG. 3. Current noise spectrum $S_I^{1/2}(f)$ (left-hand ordinate) measured at a current of 275 μA. Right-hand ordinate shows current noise spectrum normalized to the current I.

We recalibrate the look-up table whenever the load is changed. Even if the load remains the same, however, small offset drifts introduce inaccuracies in the table from day to day. To eliminate this error, the software first sets the current from the look-up table and measures the actual value, as reported by the HP 34401A. It then generates a new setting to compensate for the observed error, and iterates this process until the measured current is sufficiently close (typically ± 1 nA) to the target value. This procedure provides the software with a measurement of the offset, which is used to correct the look-up table for subsequent settings. Our current settings are thus immune to errors due to either nonlinearity in the potentiometers or overall drift in the circuit, relying only on the accuracy of the HP 34401A.

III. RESULTS

Figure 2 illustrates the automated control of the source, together with the long-term stability of the current. Curve (a) represents the output of one channel which was set initially to 750 μA, without any further control. We observe a pronounced drift with a periodic behavior which is caused by the daily temperature variation of a few degrees Celsius inside the shielded room; we believe the potentiometers to be the dominant source of this drift with some additional contributions from the OPA 627 amplifier and from the load resistances. The total current variation is 50 ppm (parts per million), with a maximum slope of 4 ppm/h. Curve (b) is measured in the same configuration, but with automated control, which consists of a single current measurement and a subsequent readjustment every 10 min; this is the usual procedure for our qubit experiments. No data are acquired during the adjustment. This method reduces any drift to a level below the noise floor of about 4 nA p-p (5 ppm), measured with a 0.5 Hz sampling rate. This current noise is determined by the voltage noise of the instrumentation amplifier and the HP voltmeter, and is not intrinsic to the current supply.

To characterize our source in the low-frequency range more precisely, we used a spectrum analyzer to measure the voltage noise across the load resistor while current is flowing
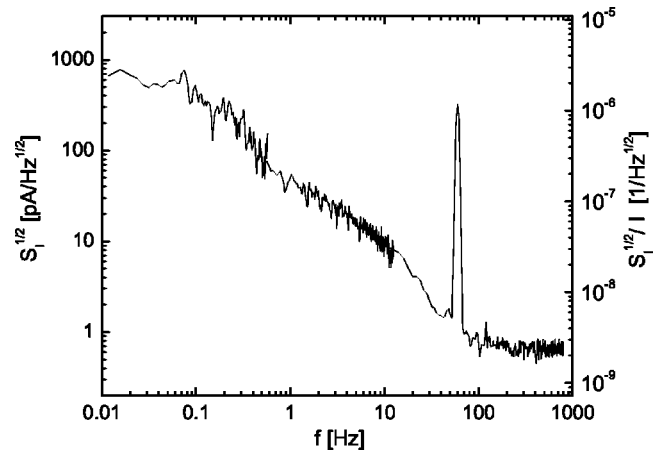
through it; the spectrum is shown in Fig. 3. The noise below about 100 Hz has a $1/f^2$ power spectrum characteristic of a drift; the size of this drift is consistent with our time-domain observations discussed above. The pronounced 60 Hz peak is an artifact of connecting the spectrum analyzer, and is not generated by the current supply itself. Neglecting the 60 Hz component and extrapolating a $1/f^2$ noise spectrum for frequencies below 10 mHz, we calculate the integrated current noise I_n for an output current of 275 μA from the data of Fig. 3, and find $I_n \approx 725$ pA (2.6 ppm) over the frequency range 1.7 mHz to 10 Hz. This frequency range is chosen to extend to the lowest frequency corresponding to the longest timescale in our experiment, that is, the 10 min period required for measurement of a complete spectrum. The corresponding decoherence time τ_φ is given by[6]

$$\tau_\varphi = \frac{d\Phi_q}{df} \frac{1}{\Phi_{q,n}} = \frac{d\Phi_q}{df} \frac{1}{MI_n}. \tag{1}$$

Here, Φ_q is the flux in the qubit, f is the frequency, and $M \approx 5.3$ pH is the mutual inductance between the flux line
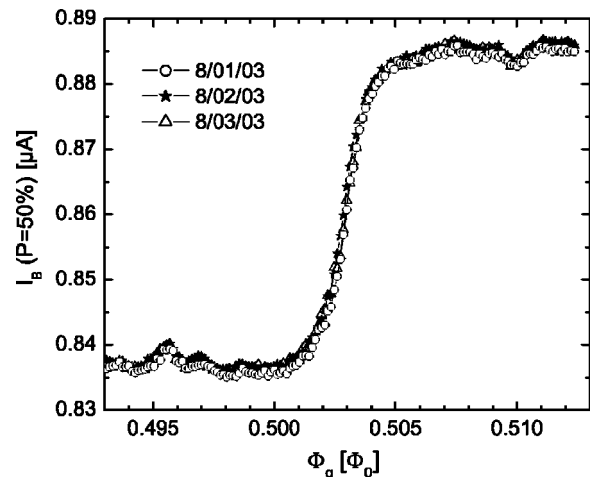

FIG. 4. Transition between the two flux qubit states measured on three consecutive days. Vertical axis shows the bias current I_B at which the readout SQUID has a 50% switching probability P versus the flux Φ_q in the qubit. The qubit and SQUID were enclosed in a superconducting cavity.

and the qubit. Using the measured value $d\Phi_q/df \approx 0.47$ mΦ_0/GHz from our qubit spectroscopy, we obtain $\tau_\varphi \approx 250$ ns. This time is an order of magnitude larger than the longest value of τ_φ yet reported in flux qubit experiments.[7] Thus, the current noise of the current supply should not be the limiting source of decoherence in current flux qubit experiments.

This current source enables us to perform detailed investigations of flux qubits that extend over several days. Figure 4 illustrates the reproducibility and long-term stability of our experiment by displaying the qubit transition measured on three consecutive days. The change in flux is less than 5 $\mu\Phi_0$. The residual small variations in I_B ($P=50\%$) arise from a change in critical current due to temperature variations of the qubit and SQUID of a few millikelvin.

Two potential improvements could be made to our current design. First, we could incorporate temperature regulation to reduce thermally induced drifts, which appear to be the dominant source of drift. Second, we could use a fourth potentiometer as a "superfine" adjustment. However, to take advantage of this precision we would require an 8-digit voltmeter, rather than the 6.5-digit instrument we currently use.

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