A FLUX LOCKED CURRENT SOURCE REFERENCE †

W. L. Tew and E. R. Williams
National Institute of Standards and Technology *
Gaithersburg, MD 20899 USA

Abstract

The quantization of flux in a closed superconducting circuit is used to provide a stable reference current. A 10 mA current source is coupled via a toroidal transformer to a dc SQUID input and the resulting signal fed back as an error current. The result is a net current that exhibits stability of 1 x 10^{-9} per hour and is quantized with a step size of 59.4 nA. This current is sourced through a precision 100 Ω resistor and compared against Zener and standard cell voltage references.

Introduction

The ideal suitability of Superconducting Quantum Interferencr Device (SQUID) systems for current controllers has long been recognized [1]. The technique of locking an external dc current to the magnetic flux from a persistent superconducting current was first demonstrated by Gallop [2]. Weyand has constructed similar systems using second order magnetic gradiometers as flux transformers [3]. As an alternative technique, smaller currents may be directly injected into a SQUID input and comparably stabilized. This approach was realized at the Electro-technical Laboratory by Sakamoto et.al. [4]. With or without an intermediate transformer and persistent current, the external current is still being locked to a particular flux quantum and will exhibit stepwise stability. Short term stability of 1 x 10^{-9} is possible in most cases when the systems are built around suitable commercial SQUID detectors.

We have built such a flux locked current source using a toroidal flux transformer and a dc SQUID. The goal is to realize a practical system for the purposes of standards calibration in fundamental electrical metrology. When combined with a stable precision resistor, the system has the potential for greater stability than other secondary voltage references. The most important issues are then the short term-stability and long-term reproducibility of the current under various conditions.

Design Considerations

Consider a closed superconducting circuit such as would be used for a dc flux transformer. The quantity that is quantized in this circuit is the fluxoid Φ_s defined as

$$\Phi_s = \int\int \boldsymbol{B}\cdot \mathrm{d}A + \mu_o \lambda_L{}^2 \int \boldsymbol{J}_s \cdot \mathrm{d}\boldsymbol{l} \,,$$

where $\boldsymbol{B}\cdot\mathrm{d}A$ is the magnetic flux linking the circuit, J_s is the circulating supercurrent and λ_L is the London penetration depth. The first term is by far the dominant contribution in any macroscopic circuit and contains the magnetic signal to which an external current would be coupled. The second term represents the contribution from the screening currents for which $J_s \sim (\lambda_L)^{-1}$. Since the sum of the two terms is quantized, changes in the distribution of screening currents can appear as changes in the flux. Thus, in addition to changes brought about through thermal expansion, the flux linkage is also temperature dependent for finite values of J_s via the temperature dependence of λ_L. It is then advantageous to bias a superconducting reference circuit at $J_s = 0$.

To couple the flux of the external circuit to the superconducting circuit a toroidal geometry offers several advantages. The complete enclosure of flux in an ideal toroidal current sheet is desirable for rejection of common mode fields and relative immunity to dimensional changes in the external circuit windings. In practice a wire wound toroid only approximates this ideal current distribution since some flux leakage occurs between the individual windings. The total self inductance L_t of a real wire wound toroid of rectangular cross section can be written as a sum of the ideal current sheet inductance L_s, a term representing the flux linking each separate turn of wire L_N, and a small term $L_w \le \mu_o \lambda_L$ for the contribution from any flux within the wire itself. These terms are

$$L_t = L_s + L_N + L_w$$

$$L_s = \frac{\mu_o}{2\pi} N^2 h \ln\frac{b}{a}$$

$$L_N = 0.332 \frac{\mu_o}{2\pi} N l$$

where N is the number of turns, l is the wire length per turn, h is the toroid height and a and b are the inner and outer toroidal radii [5]. For most practical dimensions L_N is an appreciable fraction of L_t. Thus, as a supplement to the transformer it is desirable to use overlapping, insulated superconducting shielding, as is standard practice in cryogenic current comparators [6]. This significantly improves the stability performance of the transformer [7]. However, depending on the amount of net flux linking the transformer, it will have a temperature coefficient via $\lambda_L(\mathrm{T})$.

An important parameter of a flux locked current source is the current step size I_o. This is simply a function of the flux quantum Φ_0, the SQUID input coupling efficiency or mutual inductance M_{sc}, and the current gain G_i of the flux transformer or

$$I_o = \frac{\Phi_0}{G_i M_{sc}} \,.$$

Typically $M_{sc} \approx$ 20nH or about 10 Φ_0/μA. This step size should be as small as is practical given the size of the reference current to be stabilized and one's ability to

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* Electronics and Electrical Engineering Laboratory, Electricity Division, U.S. Department of Commerce, Technology Administration.

resolve the steps with a precision resistor and digital voltmeter (DVM). It is perhaps most important that the current source in the open-loop state have short term fluctuations that are small compared to the chosen step size in order that the flux-locked loop remains locked. Thus, a few ppm is a practical lower limit.

Experimental System

The flux transformer is formed by a pair of toroidal windings. The external current passes through the primary windings and the secondary windings are connected to the SQUID input. The secondary windings are a single layer of 120 turns NbTi alloy wire held onto a notched glass-ceramic former. A return loop to compensate for the pitch of the windings is placed near the center of the former. The former has a square cross section with inner and outer diameters of 40 and 36 mm respectively. These windings are surrounded by an overlapping, insulated Pb foil shield. The primary windings are 380 turns of polytetrafluoroethylene insulated Cu wire in 4 alternating layers, which at 4K has a resistance of less than 1 Ω and a self inductance of about 70 μH. The complete transformer has a dc current gain of $G_i \approx 1.85$ at 4.2 K.

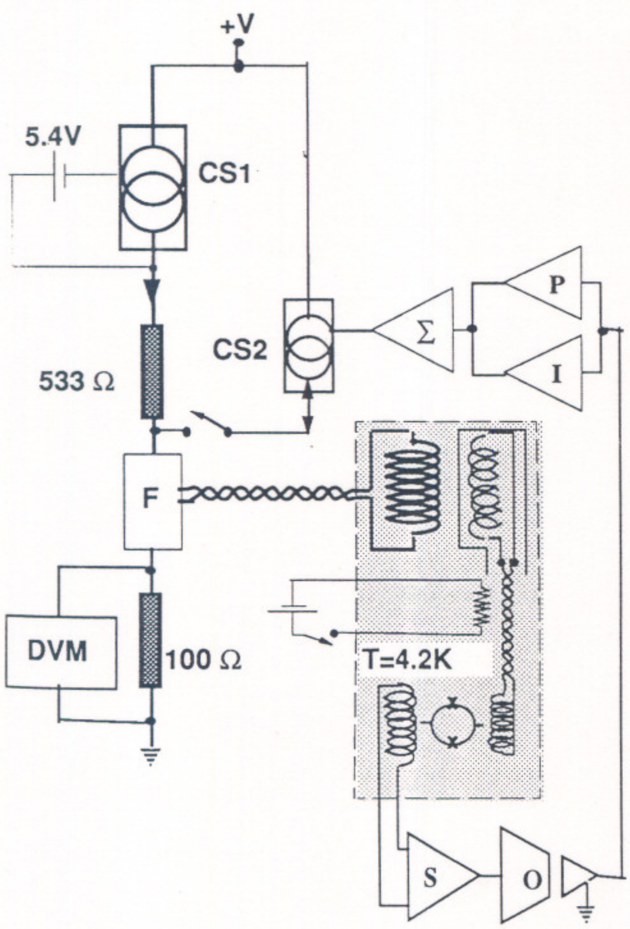

Figure 1.

A block diagram of the system is shown in figure 1. The main current source (CS1) is a high gain 10 mA unipolar source with a 5.4V Hg battery reference. It has a drift rate of 1 to 5 ppm/hour and a noise density of about 2 nA/√Hz . A single pole passive filter (F) with a 3dB point of 30Hz is required at the primary input in order to maintain a suitable signal to noise ratio. The error signal is derived from the SQUID (S) output with a typical sensitivity of 8.6 V/μA. The signal is then fed back through an optically coupled isolation amplifier (O). A parallel proportional (P) and integral (I) stage is summed (Σ) into the input of a bipolar current source (CS2) which feeds the signal back as a current returning to ground. With proper frequency compensation from the P/I stage, it is possible to achieve loop gains of 40dB at f≤1 Hz and maintain stability.

Results

Our system has a step size of 59.4 nA or about 6 ppm. The closed loop error signal indicates that the net current drift is less than 10pA in several hours. Occasional rf interference can momentarily unlock the system and allow the current to jump by multiples of I_0. However, it is always possible to reset the integrator and re-lock onto the same step. The particular step can only be determined by accurately measuring the potential drop across the precision resistor. Thermal offsets can be eliminated by reversing the current through the resistor. Comparisons of the current source with various voltage reference standards are underway to determine the long term reproducibility of the system.

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