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1:30000 CRYOGENIC CURRENT COMPARATOR WITH OPTIMUM SQUID READOUT

E. Bartolomé[1], J. Sesé[1], G. Rietveld[2], J. Flokstra[1], C. Rillo[3], A. Camón[3], H. Rogalla[1]

[1]Low Temperature Division, Applied Physics Department, University of Twente, 7500 AE Enschede, The Netherlands
[2]NMi Van Swinden Laboratorium, Dept. Electricity and Magnetism, 2600 AR Delft, The Netherlands
[3]ICMA, CSIC-University of Zaragoza, 50009 Zaragoza, Spain

Abstract

We developed a 1:30000 Cryogenic Current Comparator for SET current amplification. A dedicated low-noise, directly-coupled SQUID was used for the readout, which allowed reaching a sensitivity close to ideal. The ratio error was $<9\times10^{-9}$. The CCC-SQUID equivalent current input noise was 3.0 fA/Hz$^{1/2}$, measured down to 0.1 Hz.

Introduction

The future establishment of a quantum current standard relies on the very precise amplification of the very small (1-10 pA), quantized current provided by a Single Electron Tunneling device, with the help of an ultra-sensitive, large-ratio Cryogenic Current Comparator [1] with SQUID readout. The current quantum standard could then be combined with the existing resistance and voltage quantum standards to close the quantum metrological triangle of electrical units [2]. The final current resolution of the CCC-SQUID system (provided that all external sources of noise can be properly shielded) depends on the SQUID noise, and the efficiency of the coupling between the CCC and the SQUID. Usually, the CCC overlapped tube is coupled to the SQUID via a superconducting flux transformer. We showed [3] that perfect coupling could be achieved connecting the CCC directly to the SQUID input coil, in which case the optimal current noise could be achieved:

$$\left\langle I_P^2 \right\rangle^{1/2} = \frac{1}{N_{CCC}} \sqrt{\frac{8\varepsilon}{k_{sq}^2 L_{CCC}}}, \qquad (1)$$

where k_{sq} is the coupling constant between the SQUID washer and input coil. To minimize $\langle I_P^2 \rangle^{1/2}$, the CCC should have a large number of primary turns N_{CCC} and maximal self-inductance L_{CCC}; the SQUID should have minimum energy resolution and input coil inductance L_i close to the value of L_{CCC}. In this paper we present the integration and characterization of a complete,1:30 000 CCC with optimal SQUID readout.

Set-up

A schematics of the cryogenic part of the system is shown in Figure 1. The CCC, with 1 turn overlap, contains the following sets of windings: A: 1, 1, 2, 4, 4, 10, 10, 20, 20, 40, 40 turns; B: 100, 100, 200, 400, 400, 1000, 1000, 2000, 4000, 4000 turns; C_1: 10000 and C_2: 10000 turns. The maximum amplification ratio available is thus 1:33351. The windings are made of 70 µm thick insulated Cu wire. The inductance of the unshielded CCC as a function of frequency was measured at room temperature; $L_{CCC}(f)$ presented a resonant peak at ~1.7 kHz excited in the many-turn CCC circuit. The CCC was completely surrounded by a Pb shield. Due to the image effect, the inductance of the shielded CCC, $L_{CCC,eff}$, is smaller than that of the unshielded one. The effective self-inductance measured at room temperature with an "eddy current" method [4] coincided with the value calculated with a finite element program, $L_{CCC,eff}$=55 nH. A home-made Nb/Al dc SQUID [5], with input coil inductance L_i=45 nH close to $L_{CCC,eff}$ was used. The noise in the white region (~7 $\mu\Phi_0$/Hz$^{1/2}$) was dominated by the SQUID commercial readout electronics; at low frequencies however the noise was given by the SQUID, and amounted only ~11 $\mu\Phi_0$/Hz$^{1/2}$ at 1 Hz (Figure 2). Annealed Nb wires, wedge bonded to the SQUID input coil paths and soldered by spot welding to the SQUID module Nb blocks were used. A very low inductance (<1 nH/m) lead foil was used to connect the SQUID module to the CCC. The SQUID module was shielded by two concentric, Nb and Pb shields. The whole CCC-SQUID was fixed at the end of a rigid insert, and surrounded by a second lead and cryoperm shields. The wires carrying small (C_1, C_2) and high (A, B) currents were separated to avoid possible crosstalk. Two 10 MΩ resistors in the cold were soldered to the C_2 winding, to facilitate applying a small current. The A, B windings were available at two 20-pin Lemo connectors, while the C_1, C_2 windings were connected to

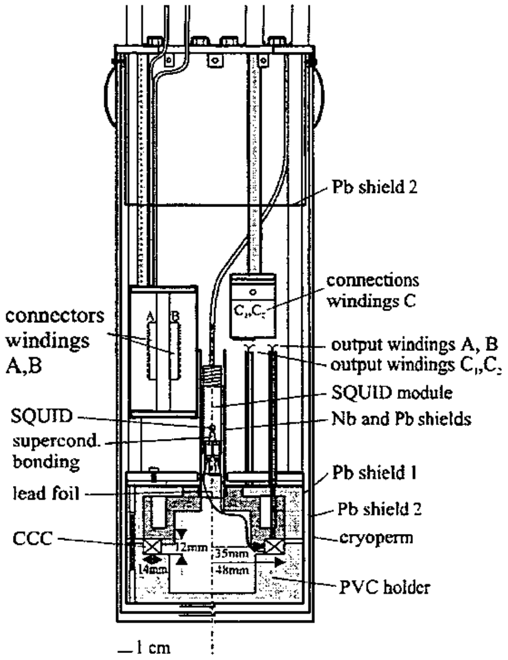

Figure 1- Schematics of the >1:30000 CCC-SQUID.

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triax connectors. A battery powered current source was used to apply (manually) a variable current of either 0-26.4 μA or 0-11.8 pA to the windings.

Measurements

The characteristics of the SQUID directly connected to the CCC were measured. The voltage period corresponding to 1 Φ_0 was 5.5 V, an intermediate situation between having the SQUID input coil leads open (4.5 V for 1 Φ_0) or shorted (9 V for 1 Φ_0). In contrast to the normal direct V-Φ curve, the demodulated V-Φ curve was affected by superimposed large frequency signals, and was very distorted as consequence of vibrations (caused by on-purpose ticking of the cryostat or vibrations of the floor), and acoustic noise. This behavior results from the appearance of LC resonances in the multi-turn CCC, excited by the 500 kHz modulation frequency signal of the SQUID readout electronics, that couples back to the flux transformer. The demodulated V-Φ curve and the noise spectrum contains thus all the excited resonant peaks corresponding to the different N-turn windings, with dominance of a ~1.7 kHz peak coming from the largest coil. The resonant phenomena did not prevent the operation of the CCC-SQUID in internal feedback mode.

The current sensitivity was measured i) in open loop, from the flux shift of the demodulated V-Φ curve when an increasing current from 0 to 26.4 μA was applied to a 1-turn winding; and ii) in closed loop, from the SQUID FLL output when a current of 4.3 μA was applied. The result in both cases was the same (S=2.3 μA.turn/Φ_0) and close (within 4%) to the theoretical ideal value.

The ratio error was measured by applying a current, reversed every ~5 s between 0 and 26.4 μA, to two N-turn windings, connected in series opposition. No error signal could be detected within the SQUID noise. Using two 1000 turn windings we obtained that the ratio error will be smaller than 9.10^{-9}. Thus a sufficiently low ratio error is achieved, even if the primary windings were made of Cu instead of superconducting wire.

The noise in FLL of the SQUID connected to the CCC was measured. At high frequencies, the system noise spectrum shows the resonant behavior already commented. However, at lower frequencies, a flat noise level of ~45 $\mu\Phi_0/\mathrm{Hz}^{1/2}$ was measured, without trace of 1/*f* noise down to 0.1 Hz. This level of noise would correspond to a current input noise (for a 33351-turn winding) of $<I_P^2>^{1/2}$~3.0 fA/Hz$^{1/2}$. From Figure 2 it can be concluded that connecting the CCC only added white noise, and not significant 1/*f* noise. The corner frequency of the CCC-SQUID system (<0.1 Hz) is directly determined by the SQUID 1/*f* noise behavior. Despite the shields used, the system noise was still dependent on the environmental magnetic noise conditions. To measure the noise at very low frequencies, the FLL output, filtered at 1 Hz, was recorded during ~6 min. A current standard deviation per turn of σ_I=2.3 fA was obtained.

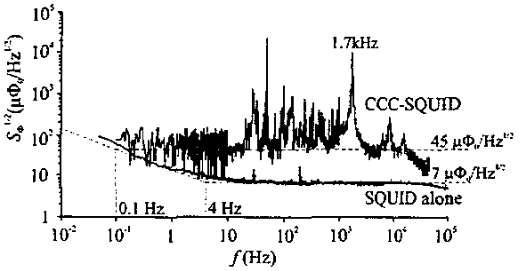

Figure 2- Flux noise of the SQUID with the CCC connected and alone.

Finally, we injected a 11.8 pA current (simulating the SET current), turned from 0 to +I every ~30 s, to the C_2:10000-turn winding. The current standard deviation was σ_I=38 fA, larger than what should be expected if the noise was only due to the CCC-SQUID (~10 fA), indicating that the current source and connecting cables added noise to the system and have to be optimized.

We estimated the current uncertainty that could be reached in the measurement of a SET current with the present system. The SET current could be reversed at a frequency f_{S1}~f_c=0.1 Hz, and the CCC-SQUID output signal recorded at a frequency f_{S2}~0.2 Hz. The measurement bandwidth would be in the white noise region. If we define "one measurement" as the record of one single cycle "+I, 0, -I, 0, +I", from which the current can be determined as [(+I)-(-I)]/2, after a total time of e.g. t_T=2 h, a number N_{rep}=720 of cycles would be recorded. The current standard deviation of the mean would be:

$$\sigma_{I,av} = \frac{\sigma_I}{\sqrt{N_{rep}}} = \frac{\left\langle I_P^2 \right\rangle^{1/2} \sqrt{BW}}{\sqrt{N_{rep}}} \approx 35\,\mathrm{aA}. \qquad (2)$$

Hence the final current uncertainty $u_I=\sigma_{I,av}/I_{SET}$, that could be reached in the amplification of a 1-10 pA SET current would be $u_I \approx 3.10^{-5}$-10^{-6} respectively. This levels are comparable to recently published results [6]. If Surface Acoustic Wave (SAW) devices were available that could give accurate quantized currents of 1 nA, an uncertainty of 10^{-7} might be reached.

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