Ultra-low-drift and very fast dc SQUID readout electronics

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Abstract. High-slew rate and thermo-stable readout electronics for dc superconducting quantum interference devices (SQUIDs) is presented. This electronics represents an optimum combination of the most important parameters for the SQUID-system user. In the new flux-locked loop (FLL) - unit design we have decreased a voltage white noise level down to the 0.32 nV/Hz\(^{1/2}\), with a flicker noise corner frequency of ~0.1 Hz. By making use of electro-thermal feedback in the first stage amplifier, and multi-loop conventional feedback throughout the whole amplifier we have achieved a very low thermal drift <10 nV/K for T= 20 – 65 °C. FLL gain stability is improved down to ~1% for the temperature range 10 – 60 °C and for 5 V (peak-peak) ± 30% of the power supplier voltage range. The maximum gain bandwidth product of the FLL-unit was increased 10 times up to ~5 GHz. In turn, we could reach more than 10 MΦ/s slew rate while using a conventional LTS SQUID (connected to the FLL by a 1.2 meter-length twisted pair), with a maximum voltage of the field–to-flux transfer function of ≥60 µV (peak-peak). At the same time, we reduced by 40% the number of chips used in the FLL unit.

1. Introduction
Every year appear new tasks and areas for Superconducting Quantum Interference Devices (SQUIDs) -based systems [1, 2]. Correspondingly requirements on the sensitivity and speed of read-out electronics for SQUID-systems increase. Commonly for linearization of system transfer function a flux-locked loop (FLL) is used [3]. Presently direct-coupled technique for SQUID-readout demonstrated optimum combination of high-speed operation and sensitivity [4 - 6]. Recently, we have developed several very fast and sensitive systems for low- and high-T, SQUIDs which are able to reach more than 3 MΦ/s slew rate with standard dc SQUIDs and ~ 0.8 meter connecting line between room temperature electronics and the cryogenic part [4, 5].

The use of direct-coupled technique demands a particular requirement to the thermo-drift of the amplifier’s input stage. The principles described in Ref. [7] are used in our previous design, which demonstrated down to ~30 nV/K temperature coefficient between -10 and 50 Celsius degrees.

However, the tasks of increasing the velocity, dynamic range, long-time and thermal stability of SQUID-systems still remains an issue of the day. Here we presented the next design of our readout electronics, which is able to provide combination of a very important parameters for the SQUID-system user. This system with 1.2 meter connecting line demonstrated more than 10 MΦ/s slew rate at frequency ~20 kHz, and temperature coefficient below than 10 nV/K.

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2. **Main features of readout electronics**

The FLL-unit contains about 100 discrete surface-mount components that are placed on double-sided board with dimensions of 8.4 cm × 2 cm (see figure 1). FLL-unit is mounted in aluminum case and connected via ~1.2 m shielded twisted pair to the SQUID sensor. Electronics is powered by ±2.5 V power sources, and consumes about 220 mW power. Signal from FLL output is amplified (10 times) by additional buffer amplifier which is placed in the control unit (see figure 2) and provides ±10V output voltage range.

Simplified functional diagram of the entire readout electronics is presented in figure 2. Electronics design is based on high-symmetrical differential circuitry solutions for all its blocks and parts including the output buffer. In comparison with our previous (completely transistor-based) design the second stage of the amplifier designed with using of one-chip dual current feedback operational amplifiers. That results in an increase of the maximum gain-bandwidth product of the FLL-unit of about 10 times up to ~5 GHz. Therefore the maximum slew rate of system is improved up to ≥10 MΦ/s with 1.2 meter connection cable. An integrator unit is based on the earlier described concept [4, 5]. A voltage controlled FLL/Reset switch disconnects in the reset mode the feedback resistors $R_{FB1,2}$ and reduces the FLL amplification from ~60,000 to 1,000.

To reduce the drift caused by change of the wire resistance between SQUID and FLL-unit with temperature we provided possibility (not shown in the figure 2) to work with a three- and four- point SQUID biasing scheme.

The input stage of the amplifier is constructed similar to our previous systems [4, 5]. But in order to improve its thermal stability we introduced an additional voltage stabilizer for biasing of the input transistors and applied a circuit which compensates the gain variation for the temperature range between 20 – 65 °C. As a result we have decreased the common thermal coefficient of electronics down to <10 nV/K. The temperature measurements were performed with a shorted amplifier input. The amplifier was placed in a aluminum box with overall dimensions of 16 cm × 10 cm × 3 m. Temperature was maintained by the external heater and was measured with a semiconductor thermometer inside the box. As well, measurements demonstrated a ±1% of FLL gain stability for the whole temperature range 10 – 70 °C and for ±20% of power supplier voltage deviation.

In comparison with our previous design we, as well, slightly improved the voltage noise performance of amplifier down to the ~0.32 nV/Hz $^{1/2}$, with a flicker noise corner frequency of ~0.1 Hz.
Current white noise level is \( \sim 7 \text{ pA/Hz}^{1/2} \) and \( \sim 40 \text{ pA/Hz}^{1/2} \) at 0.1 Hz are comparable with our previous electronics.

**Table 1.** Parameters of the SQUIDs and system performance.

| Parameter                                              | Sensor type and number                      |
|--------------------------------------------------------|---------------------------------------------|
|                                                        | Current sensor (2\(^{nd}\) order SQUID gradiometer). |
|                                                        | VC1-1.0#B0019                               |
|                                                        | SQUID magnetometer.                         |
|                                                        | ML2H-1499#296                               |
| Voltage swing \( V_{pp}, [\mu V] \)                   | 45                                          | 65                                          |
| Transfer coefficient in FLL-mode \( \delta V/\delta \Phi_s, [\mu V/\Phi] \) | 69                                          | 28                                          |
| Mutual inductance between feedback coil and SQUID \( M_f, [\text{pH}] \) | 140                                         | 370                                         |
| White flux noise spectral density \( S_{\Phi^{1/2}}, [\mu \Phi/\text{Hz}^{1/2}] \) | 2.2                                         | 2.2                                         |
| Field sensitivity \( B/\Phi_s, [\text{nT}/\Phi_0] \)  | 4.95                                        |                                             |
| Mutual inductance between input coil and SQUID \( M_c, [\text{nH}] \) | 2.5                                         |                                             |
| System maximum dynamic range \( D, [\text{dB}] \)     | 156                                         | 170                                         |
| System bandwidth \( f_{3dB, FLL}, [\text{MHz}] \)     | 8                                          | 4.8                                         |
| System slew rate \( \dot{\Phi}_{\text{max}} @ 10-50 \text{ kHz}, [\text{M} \Phi/\text{s}] \) | \(~4~\)                                      | \(~10.5~\)                                   |

### 3. SQUID measurements

New FLL unit was tested with several low-\( T_c \) SQUIDs. In table 1 the main parameters of two SQUID sensors are summarized.

![Figure 3. Flux noise spectrum of SQUID VC1-1.0#B0019.](image)

![Figure 4. Flux noise spectrum of SQUID ML2H-1499#296.](image)
All noise measurements were conducted in a μ-metal and Nb-superconducting screen. Noise spectra were measured with a Fast Fourier Transformation analyzer HP-35670B for frequencies below than 50 kHz, and a network analyzer HP-4396B for higher frequencies.

Flux noise spectral density measured for the SQUID current sensor we present in the figure 3. The setup for this noise measurements correspond to the system slew rate ~4 MΦ/s for the frequency range between 10 - 50 kHz. The excessive disturbances at the frequency of 50 Hz and its harmonics can be explained by provisional features of our setup (aluminum box with FLL-unit was open during the measurements).

In the figure 4 we present the noise spectrum for the magnetometer ML2H-1499#296. System slew rate in this case is higher than for first sensor and equal to ~10.5 MΦ/s. This can be explained by higher voltage swing of second SQUID and the higher mutual inductance $M_f$ in comparison with the current sensor SQUID.

4. Conclusion
We designed and tested very fast, low drift and ultra-thermo-stable readout electronics for dc SQUIDs. This readout is able to provide slew rate more than 10 MΦ/s with ordinary SQUIDs ($V_{pp}$~65 µV) and more than 1 meter-length cable between room-temperature electronics and cryogenic part.

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