A 1-MHz low noise preamplifier based on Double Relaxation Oscillation SQUIDs

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Abstract — **A low noise and wideband preamplifier based on Double Relaxation Oscillation Superconducting Quantum Interference Devices (DROSs) has been realized. A major advantage of a DROS is that it can be operated in a simple flux locked loop using direct voltage readout without flux modulation. So far, biomagnetic measurements performed in our group required only a limited bandwidth smaller than 100 kHz. Other applications, like for instance readout of radiation and particle detectors, demand a larger bandwidth. In this paper, we will discuss our efforts aimed at increasing the operational bandwidth of a DROS in flux locked loop. Presently, a flux locked loop scheme with a -3 dB bandwidth of 1.45 MHz has been built. With this system a white flux noise of 8 $\mu\Phi_0/\sqrt{Hz}$ was measured with a 1/f-corner frequency of 10 Hz. The slew rate was $2.5{\cdot}10^5$ Φ_0/s. With the mutual input inductance of 6.7 nH, an input current noise of the preamplifier of 2.5 pA/$\sqrt{Hz}$ was found and a current slew rate of 80 mA/s. We will discuss the suitability of our DROS-based preamplifier for readout of cryogenic particle detectors based on superconducting tunnel junctions.**

I. Introduction

The excellent sensitivity of Superconducting Quantum Interference Devices (SQUIDs) can be of a benefit for a broad range of applications, e.g. the readout of cryogenic particle and radiation detectors. However, as a result of the small flux-to-voltage transfer of standard resistively shunted dc SQUIDs, typically of the order of 100 $\mu V/\Phi_0$, the output noise level of these SQUIDs is 0.1 nV/$\sqrt{Hz}$. This is one order of magnitude below the input noise level of present room temperature dc amplifiers. Therefore, most dc SQUID systems use a flux modulated readout scheme in combination with step-up transformers between the SQUID and the room-temperature amplifier. This flux modulation has several major drawbacks though. Since, typically the modulation frequency is of the order of 100 kHz, the measurement bandwidth is restricted to a maximum about 50 kHz. For many applications, e.g. particle or radiation detection, this limited bandwidth is a large disadvantage. Although large bandwidth dc SQUID systems (with modulation frequencies as high as 16 MHz) have been operated successfully [1], the complexity of the electronics causes these systems to be unsuitable for readout of large arrays of particle detectors. Another drawback of flux modulation is the risk of cross talk between adjacent channels in multichannel systems. As a consequence, SQUID systems operated without modulation in a direct voltage readout mode are to be preferred, since the layout of the electronics is simpler.

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With the advent of second-generation dc SQUIDs, like SQUID arrays [2], SQUIDs with Additional Positive Feedback (APF) [3] and Double Relaxation Oscillation SQUIDs (DROSs) [4], sensors systems with both a large measurement bandwidth and a low input noise can be achieved. The large flux-to-voltage transfer of these second generation SQUIDs, typically of the order of 1 mV/Φ_0, eliminates the need for complex high frequency flux modulation schemes, including step-up transformers and lock-in detection. These properties make second-generation SQUIDs suitable as wideband and low noise preamplifiers for many applications.

At the University of Twente we are developing a readout system for X-ray spectrometers based on superconducting tunnel junctions (STJs) using Double Relaxation Oscillation SQUIDs. For accurate determination of the energy of the incident X-ray quanta a current sensitivity of 1-10 pA/$\sqrt{Hz}$, in an energy band of 0.1-10 keV, is needed. For single photon counting the individual events with a typical time constant of the order of 1 μs have to be resolved, requiring a bandwidth of several MHz.

In this paper we will discuss our development of a sensitive wideband SQUID system based on DROSs. In section II the wideband Flux Locked Loop (FLL) electronics will be discussed briefly. In section III preliminary measurements of the flux-to-voltage transfer, the current noise and the overall system transfer of a DROS operated in a wideband will be presented.

TABLE I.
DROS AND FLUX LOCKED LOOP PARAMETERS

DROS	Flux-to-voltage transfer	V_Φ	=	1	mV/Φ_0
	Maximum voltage swing	$2{\cdot}\delta V$	=	58	μV
	Linear flux range	$2{\cdot}\delta\Phi$	=	~0.07	Φ_0
	Input mutual inductance	M_{in}	=	6.7	nH
Preamplifier (AD797)	Gain	G	=	10	
	Voltage noise	e_n	=	1.1	nV/$\sqrt{Hz}$
Integrator (AD797)	Integration time constant	τ_{int}	=	12	ns
Feedback	Resistance	R_{fb}	=	10	kΩ
	Feedback mutual inductance	M_{fb}	=	240	pH

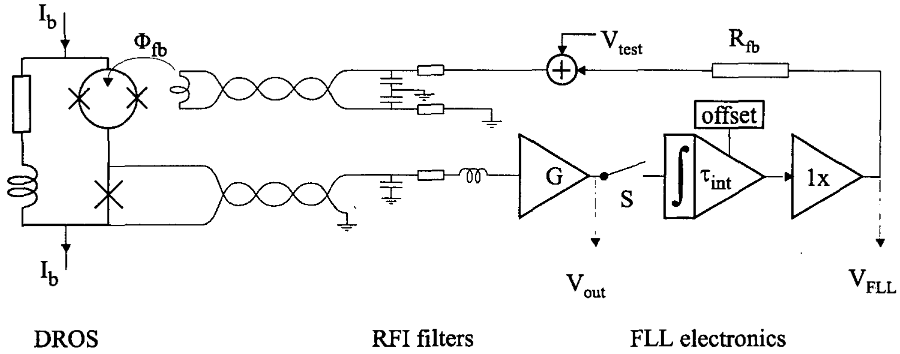

Fig. 1. Double relaxation oscillation SQUID and wideband flux locked loop electronics.

II. Setup

The scheme of the DROS and the wideband flux locked loop electronics are depicted in Fig. 1. As a non-differential preamplifier we used an AD797 opamp (Analog Devices) with a typical gain-bandwidth product of 110 MHz and a white voltage noise level of 0.9 nV/√Hz. The output of the preamplifier was integrated using a second AD797 opamp. In order to drive the capacitive load at the output of the flux locked loop constituted by coaxial cables, by parasitics in the wires and by the readout electronics, we inserted a BUF634 (Burr Brown) buffer amplifier, with a gain bandwidth product larger than 30 MHz. The phase shift introduced by the buffer at frequencies below 10 MHz is negligibly small. The output of the buffer amplifier is fed back to the single turn feedback coil of the DROS over a 10 kΩ resistor, resulting in a static feedback range of $\pm 100\ \Phi_0$. The offset is adjusted at the non-inverting input of the integrator. The DROS is biased with a symmetric current source in order to prevent an offset voltage introduced by a current in the negative voltage line. A DROS with a gradiometric layout was used as preamplifier. In Table I the relevant parameters of the DROS and the flux locked loop electronics are listed. The 2 x 25 turn input coil has a mutual inductance with the SQUID inductance of $M_{in} = 6.7$ nH. The corresponding current sensitivity of the DROS is 0.31 $\mu A/\Phi_0$ with a white noise level of 6 $\mu\Phi_0/\sqrt{Hz}$ [4]. In order to demonstrate the sensitivity of the DROS as a current sensor, the subgap structure of a Nb/Al-AlO_x/Al/Nb tunnel junction has been measured in detail [5].

At high frequencies the parasitic capacitance between the SQUID washer and the feedback coil, estimated to be 1-5 pF, causes cross talk from the feedback current to the output voltage of the DROS. In order to reduce this effect we minimized the resistance in the negative voltage and feedback lines. Both the washer and the feedback coil will thus effectively remain at zero voltage.

III. Measurements

The typical best flux-to-voltage transfer curve, as measured with our standard 100 kHz preamplifier and small band Radio Frequency Interference (RFI) filters, is depicted in Fig. 2 (lower trace). The maximum flux-to-voltage transfer corresponding with this curve is 1 mV/Φ_0, cf. Table I. The voltage modulation equals $2\cdot\delta V = 58\ \mu V$.

As the upper curve in Fig. 2a clearly indicates, the flux-to-voltage transfer of the DROS degrades when operated in a wideband with the electronics as described in Section II

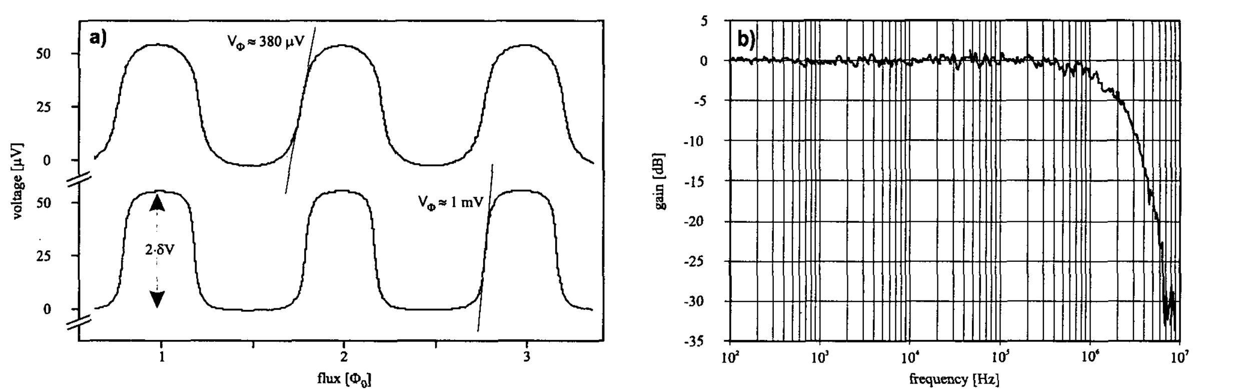

Fig. 2. a) flux-to-voltage transfer curve; upper curve depicts transfer as measured with wideband preamplifier and minimal RFI filtering ($V_\Phi \approx 380\ \mu V/\Phi_0$), lower curve presents typical best result as measured with 100 kHz preamplifier and regular RFI filtering, ($V_\Phi \approx 1\ mV/\Phi_0$). b) transfer function of flux locked loop electronics (B = 1.45 MHz).

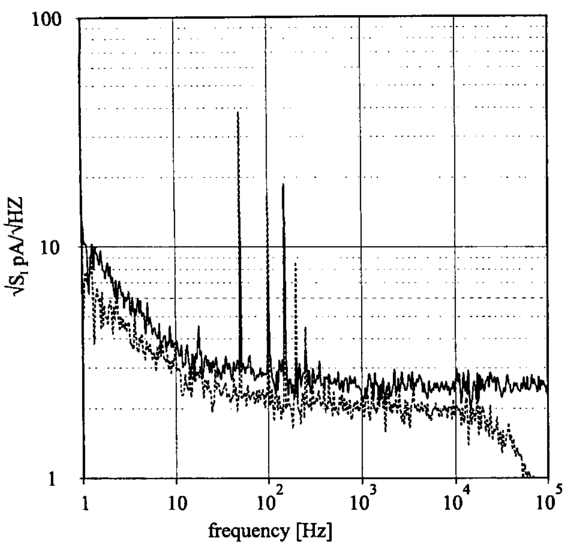

Fig. 3. Current sensitivity of DROS with standard 100 kHz FLL electronics (dashed curve) and with wideband FLL electronics (solid curve)

and with minimal RFI filtering. The flux-to-voltage transfer function presumably deteriorates as a result of RFI and the wideband white noise, which was fed back to the SQUID. As a result of the noise rounding, a maximum flux-to-voltage transfer of only 380 $\mu V/\Phi_0$ was measured. The maximum voltage modulation was not affected and remained approximately $2\cdot\delta V = 58\ \mu V$.

The frequency response of the SQUID system in a flux locked loop has been recorded using a gain-phase analyzer (HP4194A), see Fig. 2b. As Fig. 2b indicates the –3 dB bandwidth of the DROS in flux locked loop is 1.45 MHz. A slew rate of $2.5\cdot10^5\ \Phi_0/s$ was measured. Together the flux slew rate and the mutual input inductance determine the maximum rate, at which the system can track a current through the input coil without unlocking,

$$\dot{i}_{max} = \frac{\dot{\Phi}_{max}}{M_{in}} = 80\,\text{mA/s}\,. \qquad (1)$$

A white voltage noise level of the AD797 preamplifier of 1.1 nV/√Hz was measured. The 100 Ω resistor in the RFI filters of the voltage lines contributed $(4kTR)^{1/2} = 1.3$ nV/√Hz to the total noise. This results in an input voltage noise level of our electronics of 1.7 nV/√Hz. The total noise level at the output of the preamplifier with the SQUID biased on the steepest part of the V-Φ curve was 6.7 nV/√Hz and thus mainly originates from the DROS. In flux locked loop, a white flux noise level of 8 $\mu\Phi_0/\sqrt{Hz}$ was measured. With the mutual input inductance of the DROS of 6.7 nH, the input current noise of the system can be determined as

$$i_n = \frac{\Phi_n}{M_{in}} = 2.5\ \text{pA}/\sqrt{\text{Hz}}\,. \qquad (2)$$

In Fig. 3 the noise spectrum of the DROS in a flux locked loop has been plotted. The white noise level obtained with the newly developed wideband flux locked loop is somewhat larger than the flux noise of the DROS measured with the 100 kHz flux locked loop electronics. The latter noise level was 2 pA/√Hz.

IV. Discussion and conclusions

We have successfully demonstrated the ability of a Double Relaxation Oscillation SQUID to operate in a wideband flux locked loop system. For this purpose we increased the bandwidth of our flux locked loop system from 100 kHz by more than a factor of 10 to 1.45 MHz. Since the flux-to-voltage transfer was affected by additional RFI and wideband white noise, which was fed back to the SQUID, the output noise level of the system was larger than the typical best result obtained in a 100 kHz bandwidth. However, the increase of the input current noise level was small and did not exceed a factor of 1.3.

The theoretical bandwidth and slew rate of the system are given by [4]

$$B = \frac{V_\Phi G M_{fb}}{2\pi \tau_{int} R_{fb}}, \qquad (3)$$

$$\dot{\Phi}_{max} = \frac{\delta V G M_{fb}}{\tau_{int} R_{fb}} = \pi \frac{\delta V}{V_\Phi} B = \pi\ \delta\Phi B\,. \qquad (4)$$

Substituting the appropriate parameters listed in Table I in (3) and (4) yields $B = 1.6$ MHz and $\dot{\Phi}_{max} = 1.7\cdot10^5\ \Phi_0/s$. Both calculations are in reasonable agreement with the measurements. However, these calculations do not take into account the degradation of the flux-to-voltage transfer, which was measured to be $V_\Phi = 380\ \mu V/\Phi_0$. Inserting this smaller value for V_Φ into (3) yields a bandwidth of only 420 kHz. The origin of this discrepancy remains unclear. A possible explanation for this discrepancy might be found in the presence of unexpected positive phase shifts in the components of the electronics, causing a positive feedback.

For application as readout current sensor for X-ray sensors based on superconducting tunnel junctions a slew rate of about 25 A/s is needed [6] together with an input current noise level below 10 pA/√Hz. We have demonstrated that the wideband DROS based preamplifier has a noise level of 2.5 pA/√Hz, which is well below the requirements. Further improvement of the dynamic capabilities of the DROS based flux locked loop system can be achieved by either improving our electronics or by changing the geometry and characteristics of the gradiometric DROS. The wideband flux locked loop electronics can be adapted 1) by increasing the gain, G, of the AD797 preamplifier, 2) by reducing the integration time constant, τ_{int}, and thus speeding up the integrator and 3) by reducing the feedback resistance, R_{fb}. All these alterations will increase the loop gain and thus the bandwidth of the system without changing the DROS itself. The increase of the bandwidth will also directly improve the slew rate of the flux locked loop system as can be derived from (4).

Another approach to arrive at an improved dynamic performance of the system is by adjusting the DROS itself. The slew rate of our system is limited by the maximum allowable deviation from the optimum operation point of the DROS of $\delta V = 33\ \mu V$. Increasing the critical current of the junctions in the DROS will result in an increase of the maximum voltage swing of the DROS and will thus enhance the slew rate. With the present current sensitivity of the DROS of $0.31\ \mu A/\Phi_0$, the system can track signals with a maximum slew rate of 0.08 A/s. By reducing the mutual input inductance, this value can be enhanced. However, this increase of the slewing capabilities will be achieved only at the expense of additional input current noise as can be concluded from (2). A trade-off between slew rate and input noise level has to be made depending on the application of interest. Finally, the operation temperature of the DROS can be decreased. As this will lower the flux noise, the input coupling can be reduced to maintain the same current sensitivity. From (1) it is clear that a reduction of the coupling will improve the current slew rate.

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