Multichannel SQUID Magnetometry Using Double Relaxation Oscillation SQUID's

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Abstract—A highly sensitive first-order gradiometer based on double relaxation oscillation SQUID's (DROS's) for multichannel use is presented. The white flux noise level of the bare DROS's is $4.5 \mu\Phi_0/\sqrt{\text{Hz}}$ ($\epsilon \approx 275$ h). With wire-wound first-order gradiometers, having a baseline of 40 mm, the white magnetic field noise equals $4 \text{ fT}/\sqrt{\text{Hz}}$. As a result of the high flux-to-voltage transfer of the DROS's of about $1 \text{ mV}/\Phi_0$, this low noise level could be obtained with simple room-temperature flux locked loop electronics based on direct voltage readout. The relaxation frequency of the present DROS's is approximately 1 GHz. No degradation of the DROS characteristics caused by interference between relaxation oscillations in two adjacent channels has been observed, although the gradiometers are spaced by less than 1 mm. This shows that DROS's can be used in multichannel SQUID magnetometers.

I. INTRODUCTION

THE UNRIVALLED magnetic flux sensitivity of low T_c dc SQUID's allows measurements that are impossible with other sensors. In biomagnetic measurements for human brain research, for example, magnetic fields below 10^{-13} T have to be detected. Conventional SQUID magnetometers are based on nonhysteretic dc SQUID's, which have a typical flux noise level of $1\text{--}10 \mu\Phi_0/\sqrt{\text{Hz}}$, where $\Phi_0 = 2.07 \cdot 10^{-15}$ Wb is the flux quantum, and a flux-to-voltage transfer of $10\text{--}100 \mu\text{V}/\Phi_0$ [1], [2]. This results in an output voltage noise of about $0.1 \text{ nV}/\sqrt{\text{Hz}}$, which is much lower than the input voltage noise of $1 \text{ nV}/\sqrt{\text{Hz}}$ that can be obtained with low noise dc amplifiers at room temperature. To prevent amplifier-limitation of the sensitivity of a dc-SQUID magnetometer, flux modulation techniques in combination with cryogenic impedance matching circuitry are frequently used. In multichannel applications, these modulation schemes exhibit some severe drawbacks, such as limited bandwidth, crosstalk between adjacent channels, and complicated electronics. Therefore, several groups have developed new SQUID types, like dc SQUID's with additional positive feedback (APF) [3], [4], two-stage SQUID's in which the signal of the sensing SQUID is amplified by a second SQUID [5], [6], or by a series array of SQUID's [7], single-chip digital SQUID's [8], relaxation oscillation SQUID's (ROS's) [9]–[13], and double relaxation

oscillation SQUID's (DROS's) [12]–[14]. All these SQUID's enable direct readout with relatively simple room-temperature electronics. This paper deals with DROS's.

A DROS converts a magnetic flux to a voltage with a flux-to-voltage transfer that is typically 10–100 times larger than that of conventional dc SQUID's. This large transfer enables a simple flux locked loop (FLL) configuration, based on direct voltage readout at room temperature. The principle of operation is based on relaxation oscillations that are induced in hysteretic dc SQUID's. At sufficiently high relaxation frequencies, 1 to 3 GHz typically, the intrinsic noise level of DROS's is the same as that of nonhysteretic dc SQUID's [15], [16]. Recently, it has been shown that the magnetic field sensitivity of a DROS gradiometer is sufficient to detect magnetic brain signals [17]. However, until now, it was not clear whether the relaxation oscillations of one DROS channel interfere with those of an adjacent channel. This would limit the application of DROS's in multichannel magnetometers. In this paper, it is shown that the magnetic field noise level of a first-order DROS gradiometer does not depend on the operation of an adjacent DROS gradiometer channel.

II. THEORY OF OPERATION

A DROS consists of two dc SQUID's in series, shunted by a resistor R_{sh} and an inductor L_{sh} , as shown schematically in Fig. 1. The dc SQUID's are based on underdamped Josephson tunnel junctions, thus causing hysteretic SQUID I-V curves. The magnetic flux to be measured, Φ , is applied to the upper SQUID, the signal SQUID. An adjustable reference flux, Φ_{ref} , is applied to the lower SQUID, the reference SQUID. If the DROS is biased with a dc bias current I_b , relaxation oscillations can occur. During these relaxation oscillations, only the SQUID with the smallest critical current switches to the voltage state. To a good approximation, the relaxation frequency f_{ro} is given by

$$f_{ro} = \tau_{sh}^{-1} \cdot \ln^{-1} \left(\frac{I_b}{I_b - I_c(\Phi)} \right). \quad (1)$$

In (1), $\tau_{sh} = L_{sh}/R_{sh}$ is the time constant of the L - R shunt and $I_c(\Phi)$ is the smallest of the two SQUID critical currents. In each relaxation oscillation cycle, the critical current of the signal SQUID, $I_{c,sign}(\Phi)$, is compared with the constant critical current of the reference SQUID, $I_{c,ref}(\Phi_{ref})$. If $I_{c,sign}(\Phi) < I_{c,ref}(\Phi_{ref})$, the signal SQUID switches to the finite voltage state during the relaxation

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Fig. 1. Schematic overview of a DROS.

oscillations, whereas the reference SQUID stays in the zero-voltage state, so no voltage will be present between the voltage output terminal V and ground. However, if Φ is changed such that $I_{c,sign}(\Phi) > I_{c,ref}(\Phi_{ref})$, the reference SQUID switches during the oscillations, causing a sequence of voltage pulses at the output. The time-averaged value of these pulses is $V_c = V_c(I_b, \Phi_{ref})$. Typically, for I_b well above $I_{c,ref}$, $V_c = (0.5-0.75) \cdot I_b \cdot R_{sh}$. To assure that both the situations $I_{c,sign} > I_{c,ref}$ and $I_{c,sign} < I_{c,ref}$ can occur if the signal flux Φ changes, $I_{c,ref}$ has to be adjusted to a value in the centre of the $I_{c,sign}$ modulation range, simply by varying Φ_{ref} . The result is a V - Φ characteristic with a very high transfer $\partial V / \partial \Phi$ at the transition from $V = 0$ to $V = V_c$, where the critical currents of both SQUID's are equal.

The relaxation oscillations are persistent if the following operation condition is satisfied [15]:

$$\beta_c^* \cdot \left(\frac{I_b}{2I_0} \right)^2 < 1 \quad \text{with} \quad \beta_c^* = \frac{2\pi \cdot 2I_0 \cdot R_{sh}^2 \cdot C_{sq}}{\Phi_0}. \quad (2)$$

In (2), I_0 is the junction critical current, C_{sq} the SQUID capacitance, and β_c^* the effective McCumber parameter for a DROS. Combined with $V_c = (0.5-0.75) \cdot I_b \cdot R_{sh}$, (2) yields the following expression for the maximum voltage modulation depth $\Delta V (= V_c)$ that can be achieved with a DROS:

$$\begin{aligned} \Delta V_{DROS,max} &= (0.5 \cdots 0.75) \cdot I_{b,max} \cdot R_{sh} \\ &= (0.5 \cdots 0.75) \cdot \sqrt{\frac{2I_0 \cdot \Phi_0}{2\pi \cdot C_{sq}}}. \end{aligned} \quad (3)$$

Equation (3) shows that the voltage modulation depth of a DROS does not depend on R_{sh} , thus relaxing the design and fabrication constraints.

To prevent L - C resonances in the L - C - R loop formed by L_{sh} , C_{sq} , and R_{sh} , an additional damping resistor R_d can be included as shown in Fig. 1. The L_{sh} - C_{sq} oscillations that can deteriorate the DROS characteristics drastically are adequately damped if the damping parameter D satisfies the following:

$$D = \frac{L_{sh}}{4 \cdot C_{sq} \cdot R_d^2} > 1. \quad (4)$$

Since, in practical cases, $R_d \gg R_{sh}$, addition of R_d does not affect the operation criterion given by (2).

For relaxation frequencies well below the plasma frequency of the tunnel junctions (by a factor of about 50 or more), the flux-to-voltage transfer $\partial V / \partial \Phi$ of a sufficiently damped DROS is mainly determined by V_c and by the thermal spread on the critical currents of both SQUID's. Numerical simulations yield the following analytical expression for the thermally limited flux-to-voltage transfer [12], [15]:

$$\left(\frac{\partial V}{\partial \Phi} \right)_{\max} = 7 \cdot \frac{I_0^{2/3}}{(1 + \beta_{L,sign})} \cdot \frac{V_c}{\Phi_0}. \quad (5)$$

In this equation, I_0 is the junction critical current in microamperes and $\beta_{L,sign} = 2I_0 \cdot L_{sq,sign} / \Phi_0$, with $L_{sq,sign}$ being the signal SQUID inductance. Numerical simulations showed that for much higher relaxation frequencies, (5) no longer holds true.

At the points of maximum transfer, the switching probability for both SQUID's is 50%. From the voltage noise spectrum caused by this stochastic process and from (5), the following expression for the flux noise spectral density of a DROS can be derived [12], [15]:

$$\sqrt{S_\Phi} = 2.3 \cdot \frac{(1 + \beta_{L,sign})}{I_0^{2/3}} \cdot \sqrt{\frac{1}{f_{ro}}}. \quad (6)$$

In (6), $\sqrt{S_\Phi}$ is expressed in $\mu\Phi_0 / \sqrt{\text{Hz}}$ if the junction critical current I_0 is substituted in microamperes and the relaxation frequency f_{ro} in GHz. From (6), it turns out that DROS's can have the same sensitivity as comparable nonhysteretic dc SQUID's if the relaxation frequency is sufficiently high, of the order of 1 GHz typically.

III. EXPERIMENTAL SETUP

A three-channel insert for use in a fiber glass liquid helium cryostat (BTI model BMD 5) has been constructed. Most measurements were done in a magnetically shielded room (MSR, Vacuumschmelze, type AK 3B). The three wire-wound first-order gradiometers are positioned in a triangular configuration, and are spaced less than 1 mm, which is small compared to the pickup coil diameter of 20 mm. The gradiometers touch the bottom of the cryostat; to prevent mechanical tensions during cooling down, they can move in axial direction. About 15 cm above the pickup section, three DROS's are mounted in separate cylindrical Nb/Pb modules with an outer diameter of 10 mm and a length of 5 cm. The connection between each DROS-module and the room-temperature FLL electronics is made by resistive wires ($R \approx 25 \Omega$ per wire), twisted in pairs and shielded by a stainless steel tube. Each channel has its own FLL electronics in a separate aluminum box directly on top of the cryostat. The data acquisition system, outside the MSR, is connected to the system with coaxial cables.

A. DROS Layout

Fig. 2(a) shows a micrograph of the DROS's that were used, whereas Fig. 2(b) gives a schematic diagram. The Nb/Al_xO_y/Nb Josephson tunnel junctions, other Nb

Fig. 2. (a) Micrograph of an actual DROS. (b) Scheme of the actual DROS layout.

structures and the SiO₂ insulating layers are patterned by reactive ion etching (RIE) in CF₄. Resistors are structured in Al thin films by wet chemical etching in a NaOH containing solution.

The washer type signal SQUID is tightly coupled to a 25 turns input coil. The hole width is 100 μm , resulting in the theoretical values $L_{\text{hole}} = 160$ pH and $L_{\text{in}} = 100$ nH [18]. A single-turn feedback coil is included at the outside of

the input coil. From the experimental $I_{c,\text{sign}}(\Phi)$ modulation, $\beta_{L,\text{sign}}$ was estimated to be 1.3, giving $L_{sq,\text{sign}} = 240$ pH. Combined with L_{hole} , this value indicates 80 pH of parasitic inductance, probably caused by the double slit, which has a length of 250 μm and a slit width of 2 μm . The mutual inductance between the signal SQUID and the input coil, M_{in} , was measured to be 4.1 nH. With the experimental SQUID inductance of $L_{sq} = 240$ pH and the design value $L_{\text{in}} = 100$ nH, this yields a coupling coefficient between SQUID washer and input coil of 0.84. To prevent L - C resonances in the signal SQUID, the SQUID inductance is shunted with a resistor, R_w , of 3 Ω [19]. Since R_w is smaller than the characteristic SQUID impedance, given by $\frac{1}{2}\sqrt{(L_{sq}/\frac{1}{4}C_{sq})}$, L - C resonances in the signal SQUID are adequately damped. On the other hand, R_w is not so small that its Johnson noise significantly increases the intrinsic flux noise of the DROS: $L_{sq} \cdot i_n = L_{sq} \cdot \sqrt{4kT/R_w} \approx 1 \mu\Phi_0/\sqrt{\text{Hz}}$. The hysteretic $2 \times 2 \mu\text{m}^2$ Josephson junctions at the outer side of the signal SQUID washer have a capacitance of 0.25 pF each, and a critical current I_0 of 5.5 μA .

The much smaller reference SQUID has a designed inductance of 32 pH. A single turn coil is integrated on top of the reference SQUID to generate the reference flux, Φ_{ref} . The $2.2 \times 2.2 \mu\text{m}^2$ junctions have $I_0 = 6.5 \mu\text{A}$. The small SQUID inductance gives $\beta_{L,\text{ref}} \approx 0.2$, which enables a wide modulation range for $I_{c,\text{ref}}$, covering the $I_{c,\text{sign}}$ modulation range completely.

The inductive shunt, which has a design value of $L_{sh} = 1$ to 1.5 nH, is located symmetrically around both SQUID's, to prevent possible negative effects of magnetic coupling between the shunt inductance and the SQUID's. Each branch has its own resistor of 2 Ω , so that $R_{sh} = 1 \Omega$, implying $\beta_c^* = 0.017$. This small β_c^* ensures proper operation of the DROS, even for relatively high bias currents: according to (2), $I_{b,\text{max}} = 2I_0/\sqrt{\beta_c^*} \approx 85 \mu\text{A}$, yielding a theoretical voltage modulation depth ΔV of about 50 μV . According to (1), the relaxation frequency is of the order of $1/\tau_{sh} = R_{sh}/L_{sh}$, so around 1 GHz for moderate bias currents. According to (6), this value of f_{ro} yields a theoretical flux noise level of $1.7 \mu\Phi_0/\sqrt{\text{Hz}}$.

Resonances between the SQUID capacitance and the shunt inductance are damped by two damping resistors of 30 Ω each, yielding $D = 2 - 3$. The damping resistors are connected as shown in Fig. 2(b) in order to shunt the junction capacitance as directly as possible: the inductance of both SQUID loops is not a part of the damping circuit.

B. Flux Transformers

The flux transformers consist of first-order Nb wire-wound gradiometers, connected to the 25 turns input coils of the DROS's. The gradiometers, which are wound around a textile reinforced epoxy core, consist of two sensing turns and two compensation turns, separated by the baseline of 40 mm. The sensing turns have an intermediate distance of 1 mm whereas the two compensation turns are spaced by 12 mm in order to

Fig. 3. Simplified DROS flux locked loop with direct voltage read-out at room temperature.

minimize the inductance L_{pu} of the gradiometer. The diameter of the gradiometers is 20 mm, resulting in a calculated self inductance L_{pu} of $0.35 \mu\text{H}$ and a sensing area A_{pu} of 6.3 cm^2 . Inside the DROS modules, the twisted insulated Nb wires coming from the gradiometers are connected to $50 \mu\text{m}$ thick Nb bonding wires by means of small Nb blocks with screws. The superconducting connection with the input coil is made by ultrasonic bonding of these $50 \mu\text{m}$ thick wires, that have to be pretreated as described in [20] prior to bonding.

Across the input coil pads, an external R - C shunt, consisting of a 150Ω metal film resistor, R_{in} , in series with a 1-nF capacitor, C_{in} , is connected [17]. When the gradiometers are connected, the R_{in} - C_{in} shunt forms a $250\text{--}300 \text{ MHz}$ low pass filter, preventing external high frequency magnetic noise to interfere with the relaxation oscillations.

C. FLL Electronics

A schematic overview of the FLL electronics for one channel is given in Fig. 3. At the top of the insert, all leads are lowpass filtered with respect to ground by means of simple R - C filters. The cutoff frequency of the filters in the bias current and reference flux leads is 2 kHz , whereas the filters in the voltage and feedback flux leads have cutoff frequencies of 3 MHz , to enable a high bandwidth in FLL. The output voltage of the DROS is fed to a differential instrumentation amplifier based on LT 1028 op-amps. The gain of this amplifier can be adjusted from $G = 2 \cdot 10^2$ to $G = 2 \cdot 10^5$. The white input voltage noise level is about $1.8 \text{ nV}/\sqrt{\text{Hz}}$ ($5 \text{ nV}/\sqrt{\text{Hz}}$ @ 1 Hz), whereas the white current noise amounts about $2 \text{ pA}/\sqrt{\text{Hz}}$ ($30 \text{ pA}/\sqrt{\text{Hz}}$ @ 1 Hz). To minimize the effect of current noise, especially for low frequencies, the total resistance in the voltage leads, including filtering, has been kept below 80Ω . The output of the amplifier, which has a bandwidth of about 250 kHz , is connected to an integrator with an integration time $\tau_{int} = 10^{-2}, 10^{-3}$ or 10^{-4} s . The integrator output provides the feedback flux for the DROS via an adjustable feedback resistor (R_{fb}). In practice, R_{fb} was adjusted to such a value that $R_{fb}/M_{fb} = 1 \text{ V}/\Phi_0$. For testing purposes, e.g., V - Φ characterization in open loop configuration (switch S opened), a test flux, Φ_{test} , and an offset flux can be added to the feedback flux.

The simple layout of this FLL allows a large small signal bandwidth $f_{c,FLL}$:

$$f_{c,FLL} = \frac{G \cdot \left(\frac{\partial V}{\partial \Phi} \right)_{\text{DROS}} \cdot M_{fb}}{2\pi \cdot \tau_{int} \cdot R_{fb}}. \quad (7)$$

For large signals ($> \frac{1}{2}\Phi_0$) the maximum slew rate of the FLL is important:

$$\left(\frac{\partial \Phi}{\partial t} \right)_{\max} = \frac{\frac{1}{2}\Delta V_{\text{DROS}} \cdot G \cdot M_{fb}}{\tau_{int} \cdot R_{fb}}. \quad (8)$$

The three channels have one common power supply, outside the shielded room. The powerlines are split inside the MSR, to prevent excessive 50 Hz noise arising from ground loops. The ground leads of all cables traversing the wall of the MSR are connected to the MSR, as is the insert itself. With this grounding scheme, the system works even when the door of the MSR is open.

IV. EXPERIMENTAL RESULTS

The experiments that have been performed had three main issues: characterization of the flux transformers, performance tests of a single DROS gradiometer channel, and investigations of the simultaneous operation of two adjacent DROS gradiometers. Below, the results are discussed in this order.

A. Flux Transformers

DROS V - Φ curves have been recorded by feeding a current I_{fb} through the feedback coils of the DROS's. In Fig. 4, V - Φ characteristics are shown for three different cases: in the first trace (Fig. 4(a)), only the R_{in} - C_{in} shunt is connected to the input coil; the second trace (Fig. 4(b)) gives the V - Φ curve in the case of a superconductively shorted input coil; and the last trace (Fig. 4(c)) was recorded with connected first-order gradiometer. The gradiometers were shielded by a lead can around them, which was necessary to suppress the effect of Johnson noise in the radiation shields of the cryostat: preliminary measurements showed a noise level of about $30 \text{ fT}/\sqrt{\text{Hz}}$ when the gradiometers touched the bottom of the cryostat, decreasing significantly when the gradiometers were lifted a few centimeters above the bottom. As can be seen from the different periods of the traces in Fig. 4, the mutual

Fig. 4. Experimental $V-\Phi$ curves: (a) input coil open; (b) input coil shorted; (c) shielded first-order gradiometer connected. Traces (a) and (b) have been recorded at $I_b \approx 150 \mu\text{A}$, and trace (c) at $I_b \approx 100 \mu\text{A}$. See the text for more information.

inductance between the feedback coil and the signal SQUID, M_{fb} , differs for the three situations. With open input coil, $M_{fb,open} = 220 \text{ pH}$, with shorted input coil, $M_{fb,short} = 80 \text{ pH}$ and with connected pickup coil, $M_{fb,pu} = 183 \text{ pH}$. This is caused by screening of the signal SQUID inductance by the superconducting flux transformer. This effect has been used to estimate the inductances in the flux transformer circuit.

The amount of screening is reflected in the effective SQUID inductance, given by

$$L_{sq,eff} = L_{sq} - \frac{M_{in}^2}{L_{in} + L_{pu} + L_{par}} \quad (9)$$

where L_{par} is the parasitic inductance in the flux transformer, mainly formed by the inductance of the twisted wires between the gradiometer and the input coil. Assuming that $M_{fb} = k^* \cdot L_{sq,eff}$, the constant k^* can be determined from the measurements with open flux transformer: $k^* = M_{fb,open}/L_{sq} = 220 \text{ pH}/240 \text{ pH} = 0.92$. In the case of a superconductively shorted input coil, $L_{sq,eff,short} = M_{fb,short}/k^* = 87 \text{ pH}$. With shorted input coil, $L_{pu} + L_{par} = 0$ in (9). Then, the above calculated value of $L_{sq,eff,short}$ yields $L_{in} = 110 \text{ nH}$, which is close to the design value of 100 nH . Analogously, $L_{pu} + L_{par}$ can be estimated from (9), using the results of the measurements with connected gradiometers, resulting in $L_{pu} + L_{par} = 0.31 \mu\text{H}$. The fact that this is slightly smaller than the design value of $L_{pu} = 0.35 \mu\text{H}$ is mainly caused by screening of L_{pu} by the Pb can, that fits very closely around the gradiometers.

A field-to-flux calibration has been performed after removal of the Pb shielding around the pickup coils. By positioning a known ac magnetic dipole at various distances from the gradiometers, the field-to-flux transfer was measured to be $\partial B/\partial \Phi = 0.4 \text{ nT}/\Phi_0$. Here, B is the difference between the magnetic field at the position of the sensing turns and the field at the position of the compensation turns of the gradiometer. This experimental transfer value corresponds to an effective

Fig. 5. FLL noise spectra: (a) open input coil; (b) first-order gradiometer connected. Both traces have been recorded at $I_b \approx 100 \mu\text{A}$.

pickup area $A_{pu,eff} = 5.2 \text{ mm}^2$. Using

$$\Phi_{sq} = B \cdot A_{pu} \cdot \frac{M_{in}}{L_{pu} + L_{in} + L_{par}} \quad (10)$$

combined with $A_{pu} = 6.3 \text{ cm}^2$, $M_{in} = 4.1 \text{ nH}$, and $L_{in} = 110 \text{ nH}$, it follows that $L_{pu} + L_{par} = 0.39 \mu\text{H}$. This is a reasonable value in view of the design value of $L_{pu} = 0.35 \mu\text{H}$: it indicates a parasitic inductance of about 40 nH for the 15 cm long twisted leads between gradiometer and DROS module.

B. DROS Characterization

The $V-\Phi$ characteristics in Fig. 4 show a large transfer; values of up to $4 \text{ mV}/\Phi_0$ have been observed at large bias currents (of the order of $150 \mu\text{A}$, Fig. 4(a) and (b)). However, the experimental noise performance of the DROS's is optimum at lower bias currents, about $100 \mu\text{A}$ typically, corresponding to a transfer of 0.5 to $1 \text{ mV}/\Phi_0$, as in Fig. 4(c). This is in good agreement with (2), which predicts an optimum bias current of $85 \mu\text{A}$. For lower bias currents, the flux-to-voltage transfer decreases, so that amplifier noise limits the system sensitivity, while for larger bias currents, (2) is not satisfied anymore, causing the intrinsic DROS sensitivity to limit the system sensitivity, despite the high value of $\partial V/\partial \Phi$.

The positive effect of the external $R_{in}-C_{in}$ shunt across the input coil is reflected in a larger transfer and a better noise performance. The transfer improved by a factor of 3 and the white flux noise level decreased by a factor of 1.5 when the shunt was connected, probably because of damping of input coil resonances. Reduction of the value of R_{in} resulted in an increasing white flux noise level, due to the Johnson noise generated in R_{in} , despite the dc blocking capacitor C_{in} . Downmixing of high frequency noise is probably the mechanism involved.

A typical FLL flux noise spectrum of a DROS without pickup coil, with $R_{in}-C_{in}$ shunt, is given in trace (a) of Fig. 5. The white noise level is $4.5 \mu\Phi_0/\sqrt{\text{Hz}}$ typically, corresponding to $\varepsilon = 275 \text{ h}$. At 1 Hz , the noise level is $10 \mu\Phi_0/\sqrt{\text{Hz}}$. In accordance with (7), the bandwidth of the FLL is larger than 100 kHz , which is the maximum bandwidth of the spectrum analyzer (HP 3562A) that was used for the noise measurements.

The flux noise did not change significantly when the flux transformer was superconductively shorted, indicating that the

noise characteristics of the DROS are not strongly influenced by the flux transformer circuit. However, when the shielded first-order gradiometers were connected, the flux-to-voltage transfer decreased and the white flux noise level rose to about $10 \mu\Phi_0/\sqrt{\text{Hz}}$, as shown by the trace in Fig. 5(b). Probably, this is caused by RF interference, despite all precautions that were taken to minimize this source of disturbances. The right axis of Fig. 5 shows the magnetic field noise according to the experimental field-to-flux transfer of $0.4 \text{ nT}/\Phi_0$. As can be seen, the white noise level amounts about $4 \text{ fT}/\sqrt{\text{Hz}}$, increasing to $10 \text{ fT}/\sqrt{\text{Hz}}$ at 1 Hz.

C. Multichannel Operation

A possible source of degradation of DROS characteristics in a multichannel system could be crosstalk at the relaxation frequency. During the relaxation oscillations, the current through the signal SQUID oscillates between zero and the critical current of the SQUID. This oscillating current causes the net flux in the SQUID to oscillate with an amplitude of the order of $1 \Phi_0$ with a frequency equal to the relaxation frequency, so about 1 GHz in the present case. Via the flux transformer, these oscillations are transferred to the pickup section of the magnetometer, and finally, crosstalk between adjacent pick up coils can couple them to another channel, thus causing a high frequency ripple on the signal flux. Even with an $R_{\text{in}}\text{-}C_{\text{in}}$ shunt across the input coils of both DROS's, the amplitude of this ripple can be hundreds of $\mu\Phi_0$, so that interference of the two relaxation frequencies is not quite unrealistic.

In practice, when two adjacent DROS gradiometer channels were operated simultaneously, the spectral flux noise density of one channel was unaffected by the operation of the other DROS, which was biased in such a way that its signal SQUID was oscillating. Probably, the spectral impurity of the relaxation oscillation frequencies in both DROS's is large enough to "smear" the crosstalk flux over a considerable bandwidth, thus drowning it completely in the DROS noise of $4 \text{ fT}/\sqrt{\text{Hz}}$. A low frequency crosstalk via the flux transformers was clearly present: when a feedback flux of $1 \Phi_0$ was applied to one DROS, the other one detected a flux of $0.005 \Phi_0$. This crosstalk of 0.5% is a direct consequence of the small distance between the gradiometers: they are spaced by less than 1 mm.

These results show unambiguously that interference between the relaxation oscillation processes in two adjacent DROS channels does not deteriorate the DROS characteristics, despite crosstalk via the flux transformers. This opens the way to highly sensitive multichannel magnetometers based on DROS's.

V. CONCLUSION

The feasibility of a multichannel DROS magnetometer system has been investigated by constructing a three-channel DROS gradiometer setup with relatively simple room-temperature FLL electronics. Typically, the bare DROS's that are used show a white flux noise level of $4.5 \mu\Phi_0/\sqrt{\text{Hz}}$ in FLL. An external $R\text{-}C$ shunt across the input coil has a positive effect on both the flux-to-voltage transfer and the noise

performance. After first-order wire-wound gradiometers had been connected, the flux noise level increased to $10 \mu\Phi_0/\sqrt{\text{Hz}}$, probably due to high frequency electro-magnetic interference. With the experimental field-to-flux transfer of $0.4 \text{ nT}/\Phi_0$, this flux noise level corresponds to a white magnetic field noise of $4 \text{ fT}/\sqrt{\text{Hz}}$. At 1 Hz, the field noise amounts $10 \text{ fT}/\sqrt{\text{Hz}}$. The noise level is not influenced by the relaxation oscillations in adjacent channels, thus showing that DROS's can be used in multichannel magnetometers.

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