Noise analysis of DC SQUIDs with damped superconducting flux transformers

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Abstract. An analysis was performed of intrinsic noise for high-TC DC SQUID with superconducting flux transformer (FT) containing resistive elements. For a SQUID with a loop inductance of about 40 pH we observed voltage swings of ∼55 µV and a flux noise of ∼4 µΦ0/√Hz at 77 K. Inductive coupling of an 8-mm multilayer superconducting FT to the SQUID increased voltage swings to ∼70 µV due to effective reduction of the SQUID loop inductance. This also increased the flux noise to ∼6 µΦ0/√Hz, corresponding to a field resolution of ∼18 fT/√Hz at 77 K with a white noise spectrum down to frequency ∼10 Hz. The main sources of white flux noise were the Nyquist noise in the Josephson junctions and the FT, as well as the suppression of the DC SQUID voltage swings caused by parasitic capacitance between the FT and the SQUID. An ultra-low-ohmic resistor with resistance value between the flux-creep-induced resistances of superconductors (below ∼0.1 nΩ) and resistances of conventional resistors (above ∼0.1 mΩ) was developed. An RL-circuit based high-pass filter (HPF) with time constant ∼7 sec was realized and integrated in the superconducting FT. The contribution of the HPF to the noise of the sensors was measured and compared with calculated values.

1. Introduction
The direct-current superconducting quantum interference devices (DC SQUIDs) demonstrate superior sensitivity for measuring the vector components and spatial gradients of magnetic fields, as well as an ability to resolve tiny changes in large signals. These features are particularly useful and have already been implemented in many applications such as low-noise amplifiers, biomagnetic research, non-destructive evaluations, and geomagnetic exploration [1, 2]. In the case of high-TC SQUIDs with a 16-mm multilayer flux transformer (FT), a field resolution greater than 4 fT/√Hz at 77.4 K in magnetic shielding has been demonstrated [3]. However, in the presence of large background magnetic fields, the increased intrinsic noise caused by the thermally activated creep of Abrikosov vortices spoils the resolution of the sensors and limits their applications despite reduced costs and a simple cooling process in comparison with the operation of low-TC SQUIDs at 4.2 K. To some extent, pinning of the Abrikosov vortices can be improved by implementing thicker high-TC films [4]. However, this was found to be insufficient for most applications. For stable operation of sensitive high-TC SQUID sensors during measurements outside magnetic shielding a high slew rate is required of the measuring system determined by a low flux noise and large voltage swings of the SQUIDs. Additionally, high screening currents appearing in the pickup coil of the multilayer FT after large changes in external magnetic flux
should be avoided to minimize the low-frequency noise of the SQUID sensors associated with creep of vortices in the high-\(T_c\) films.

A straightforward way of increasing the voltage swings and reducing flux noise of the SQUID sensor is to reduce its inductance [5] and to inductively couple it to a multiturn input coil of a multilayer FT [6]. A theoretical and empirical analysis and suppression of noise sources originating from the superconducting FT and from its coupling to the SQUID are necessary to further improve of field resolution and stable unshielded operation of high-\(T_c\) DC SQUID magnetometers and gradiometers. For example, the damping resistors can cause an additional Nyquist noise in the FT, making it desirable to find an optimum in suppressing resonances [7]. Parasitic capacitive shunting of the SQUID by FT can also lead to significant deterioration of the voltage swings and the noise properties due to LC resonance in the SQUID [8].

The screening currents in the FT can be limited, for example, by a weak link or a Josephson junction integrated in series with the pickup loop: the so called flux dam [9]. At much smaller currents, the area of the flux dam becomes non-superconducting and dissipates the excess current. Due to the logarithmic decay of the current with time [10], it takes a long time until the flux dam completely closes and the uncontrolled flux entry into the pickup loop stops. The waiting time can be shortened by applying a compensation field or a switch [10], reducing circulating currents to a near-zero value. Such low noise corrections of screening currents for SQUID sensors with a flux dam are not trivial and they are absent in the commercially available SQUID control electronics. As an alternative to flux dams and local compensation of the Earth’s field [11], we have suggested [12] implementing an RL-circuit-based high-pass filter (HPF) integrated in the FT for passive reduction of the currents induced by slow-changing (time constant > 1 sec) background magnetic fields. For comparison, SQUIDs with a normal conducting FT have a cutoff frequency of \(\sim -10\) kHz and they are sensitive only at operation frequencies of \(-1\) MHz [13]. Another solution with high-\(T_c\) superconducting wires [14] failed to demonstrate sufficient sensitivity and was too bulky for integration into the multichannel systems.

Usually, the FT for sensitive SQUID magnetometers is produced from a closed superconducting circuit with no resistive elements introduced in series. The superconducting current can flow in such a FT without dissipation for many years. This corresponds to dissipation time constant \(\tau = L/R > 10^8\) sec and a resistance below \(10^{-16}\ \Omega\) at the inductance \(-10\) mH for a bulky ring with a diameter of \(-1\) cm. In the case of high-\(T_c\) superconductors, a flux-creep-induced resistance of \(\rho = 6 \times 10^{-13}\ \Omega\) cm exists, leading to the effective resistance \(-10^{-13}\ \Omega\) and a time constant \(\tau = 10^8\) sec for the inductance of the FT \(-2\ \mu\)H [15]. This means, that for effective dissipation of the superconducting current the flux-creep-induced dissipation time constant of the fully superconducting FT is too long. Thinning and/or degrading the superconducting film could reduce the dissipation time constant, but could also degrade the long time stability of the sensors. The flux-creep-induced resistance is strongly dependent on temperature and exponentially decreases with a reduction in the circulating superconducting current. This in turn increases the dissipation time in a manner similar to the flux dam application.

In this paper, we analyse noise properties of high-\(T_c\) flip-chip DC SQUID magnetometers intended for sensitive measurements with no magnetic shielding in the Earth’s magnetic field. These include low-inductance SQUIDs with large voltage swings and SQUID sensors with a HPF integrated in the thin-film multilayer FT.

2. Experimental

The high-oxygen-pressure sputtering technique [16] in pure (99.999 \%) oxygen at a pressure of about 4 mbar was used to deposit \(\text{BaZrO}_3\) (BZO), \(\text{SrTiO}_3\) (STO), \(\text{YBa}_2\text{Cu}_3\text{O}_{7-x}\) (YBCO), and \(\text{PrBa}_2\text{Cu}_3\text{O}_{7-x}\) (PBCO) films of the SQUID magnetometers from dc- or rf-magnetron targets with diameters of 50 mm. The films were about 2.5 \% thinner on the corners of 10 mm x 10 mm substrates and 15 \% thinner on the perimeter of round wafers of diameter 30 mm compared to the film thickness in the middle of the substrates. The deposition from larger targets and the optimized arrangement of the \(\text{Sm}_2\text{Co}_{17}\) magnets in the magnetron target holders improved the thickness homogeneity of the films.
approximately threefold compared to films produced by a non-magnetron sputtering technique as described in [16].

The deposition rate of the YBCO and PBCO films was ∼50 nm/hour while the deposition rate of the non-conducting materials was ∼30 nm/hour. The PBCO films together with STO films were used for the insulation layer in crossovers of the multilayer FTs [17] and for an integrated resonance-damping resistance in the FT. The effective resistivity of the epitaxial thin film STO insulation was thickness-dependent and was found to be ∼10^7 Ω·cm for 100-nm-thick STO films, ∼10^8 Ω·cm for 200-nm-thick STO films, and greater than 10^10 Ω·cm for 300-nm-thick STO films at 77 K. The PBCO film preserved the epitaxial growth of the heterostructural insulator layer on YBCO and provided a resistive damping of the resonances in the FT due to the much smaller resistivity compared to that of STO.

The structures were deposited at a substrate temperature of about 800 °C and then cooled down with an oxygenation step lasting one hour at 500 °C in 1 bar of pure (99.999 %) molecular oxygen. This was followed by cooling down to room temperature at a rate of 10 °C/min. The transition temperature of the YBCO films was 91 - 93 K and the critical current 3 – 6 MA/cm^2 at 77 K.

The multilayer FT and DC SQUID were produced on separate MgO substrates both buffered by a 300 nm thick epitaxial STO/BZO-bilayer [18]. In the magnetometer, the input coil of the FT was coupled in a flip-chip arrangement to the washer of the DC SQUID with a diameter of 1 mm. The flux transformers (FTs) were made on single crystal substrates up to 30 mm in diameter and were later shaped by a diamond saw and emery paper. The Josephson junctions of the DC SQUIDs were produced on 24° bicrystal substrates. The junctions were ∼2 µm wide and ∼100 nm thick. The resistance of the junctions was ∼5 Ω and the critical current ∼25 μA at 77 K. Patterning of the structures was performed by ion beam etching with the exception of the non-aqueous Br-ethanol etching of the first two layers of the multilayer FTs. AZ5214 and AZMIR701 photoresists were used for structuring with ion beam etching while Br-ethanol etching was performed with a PMMA photoresist mask [17].

Two types of high-T_c flip-chip DC SQUID magnetometers were prepared and investigated in this study: (type A) with the superconducting multilayer FT containing only pickup and input coils (see Figure 1) and (type B) where the superconducting multilayer FT contained an integrated passive HPF as an ultra-low-ohmic resistor R placed in series with the coils of the FT (see Figure 2). The PBCO film in the PBCO/STO heterostructural insulator is used for damping of resonances in the FT. This heterostructural insulator is represented in Figure 1 as integrated resonance damping resistors and a capacitor. They are not shown in Figure 2 but also present in the type B magnetometers.

**Figure 1.** Sketch of type A flip-chip DC SQUID magnetometer with an 8-mm multilayer FT. The resonance damping resistors are made from the PBCO film in the heterostructural insulator layer.

**Figure 2.** Sketch of type B flip-chip DC SQUID magnetometer with an integrated HPF in the 16-mm multilayer FT.
The single-turn pickup coil of the FT in the type A magnetometer had outer dimensions of 8 mm x 8 mm and an estimated inductance of about 40 nH, while the pickup coil of the FT in the type B magnetometer had 10 turns, outer dimensions of 16 mm x 16 mm and an estimated inductance of about 8 µH. Thickness homogeneity of the films is more important for the preparation of the FT for type B magnetometers because it has multilayer structures spread over the whole substrate.

2.1. Type A magnetometers

The type A magnetometer (Fig. 1) was a HTM-8x modification of our HTM-8 magnetometer [6]. It had a similar 8-mm multilayer FT (see Figure 3) but the DC SQUID inductance was twofold lower \((L_S \approx 40 \text{ pH instead of } 80 \text{ pH})\). The 40-pH SQUID hole was a 60-µm-long and 4-µm-wide slit surrounded by an array of holes of about 2 µm in diameter. The SQUID washer was octagonal with outer diameter of about 1 mm. The DC SQUID hole and washer can be classified as the “A/C” type in Figure 11 in [19]. The geometrical and kinetic inductance of the SQUID hole and bridges of the Josephson junctions were taken into account to estimate the total SQUID inductance.

![Figure 3. Photo of the 8 mm x 8 mm multilayer FT intended for type A magnetometers.](image)

The flux sensitivity \(\partial B/\partial \Phi\) of the autonomous (i.e. without FT) 40-pH SQUID was about 100 nT/\(\Phi_0\). After the flip-chip arrangement of the SQUID and FT, the flux sensitivity \(\partial B/\partial \Phi\) of the type A magnetometer was \(-3 \text{ nT/} \Phi_0\) compared to \(-1 \text{ nT/} \Phi_0\) flux sensitivity for HTM-8 magnetometers with \(-80 \text{ pH coupled-SQUID inductance.}\)

The flux slew rate of the measurement system is equal to \(\pi \Phi f\), where \(\Phi\) is the maximal magnetic flux of the frequency \(f\), which can be followed by the measuring system without losing of the feedback lock [20]. For typical environmental electromagnetic noise in buildings (e.g. in a laboratory) the required system flux slew rate for type A magnetometers is \(-3\) times smaller than for HTM-8 magnetometers, and can be easily achieved with commercially available SQUID control electronics [21]. Tuning the operation parameters such as bias current, flux modulation amplitude, and skew, as well as locking feedback, is much easier for the type A magnetometers. The tuning procedure can be performed in our laboratory, where the peak-to-peak amplitude of power-line electromagnetic interference of 50 Hz was about 70 nT, in similar way to that performed in a magnetic shield. HTM-8 magnetometers, on the other hand, usually require an RF shield with at least more than 3 dB of suppression at 50 Hz to tune of SQUID parameters in a magnetically unshielded environment.

The voltage swing and intrinsic noise of the autonomous (without FT) DC SQUIDs were compared with those of type A magnetometers after the flip-chip arrangement with FT. For the best 40-pH DC
SQUID intended for type A magnetometers, the maximal voltage swing (peak to peak) measured was up to about 55 µV and the best flux resolution of \( S_{\phi}^{1/2} \) was as low as \( -4 \mu \Phi_0 / \sqrt{\text{Hz}} \) at 77 K (see Figure 4). The magnetic field noise was measured in a composite magnetic shield containing 3 cylindrical layers of \( \mu \)-metal combined with a twin-cylindrical-layer high-\( T_c \) superconducting shield. The residual permanent magnetic field in this composite magnetic shield was about 100 nT.

For a typical bias current \( I_B = 2I_C = 50 \mu \text{A} \) the parameter \( \beta_L = 2L_s I_c / \Phi_0 = 1 \) was found to be optimal for SQUID operation and provided the best energy resolution. The flip-chip arrangement of the 8-mm multilayer FT and the DC SQUID increased the voltage swings of the SQUID to \( \sim 70 \mu \text{V} \) but also increased its flux noise to \( \sim 6 \mu \Phi_0 / \sqrt{\text{Hz}} \) at 77 K. This corresponds to the field resolution \( \sim 18 \text{fT/\sqrt{Hz}} \) at 77 K. Possible sources of additional flux noise in the type A magnetometer were investigated. We observed, that part of the additional flux noise originated from the Nyquist noise in the superconducting FT and part from coupling the superconducting FT to the SQUID.

![Figure 4. Noise spectrum of an autonomous DC SQUID with \( L_S \sim 40 \text{pH} \).](image)

Nyquist noise of the integrated resistance for damping resonances [7] in the FT is one possible source of the additional flux noise. We used a PBCO/STO heteroepitaxial layer to construct an insulator between the superconducting films of the FT. This allowed us to provide the required epitaxial growth and insulation properties of the insulator. Thanks to its conductivity along the substrate surface, the PBCO/STO heteroepitaxial layer also served as an integrated resonance-damping resistor. As a result, the \( V(\Phi) \) characteristics of the magnetometers were sinusoidal and the estimated Nyquist noise of the resistor was below \( 2 \mu \Phi_0 / \sqrt{\text{Hz}} \) at 77 K. In a few cases possible normal-conducting micro-shorts in the insulation layer, for example, due to CuO outgrowths or defects in epitaxial growth of the insulation layer at the edges of crossovers in the input coil, can also led to an additional white flux noise of the FTs. Such obviously defect FTs were rejected from the technology line and are not considered here. The insulation layer with embedded CuO outgrowths is sensitive to mechanical damages and, hence, special treatment was necessary during the photolithography and handling of the FTs. The CuO outgrowths are required for improved transport properties of the superconducting films due to improved pinning of the Abrikosov vortices but they are usually thicker than the surrounding film.
A non-monotinous dependence of the voltage swing was observed on the coupling between the input coil of the FT and the washer of the DC SQUID. The reduction in insulation thickness first increased the voltage swing due to effective reduction of the SQUID inductance down to $L_{\text{Seff}} \approx 25 \text{ pH}$.

However, thicknesses of less than $\sim 1.5 \, \mu\text{m}$ led to a reduction in voltage swing, the appearance of two maxima in the dependence of voltage swing on the bias current, and an increase in the flux noise $S_{\phi}^{1/2} = S_{V}^{1/2} \left( \partial V / \partial \Phi \right)$. Such effects indicate that the LC-resonance in the DC SQUID loop shifted to lower frequencies as a result of parasitic capacitive shunting of the DC SQUID by the FT with a corresponding increase in the Stewart-McCumber parameter $\beta_C = 2\pi R_C C \Phi_0$ of the Josephson junctions (see e.g. [8, 22, 23]). For the bicrystal Josephson junctions, the typical value of the parameter $\beta_C$ is $\sim 0.3$ at 77 K. This value can significantly increase due to the capacitive coupling of the junctions with the return line of the multilayer FT, which covers the junctions and slits in the SQUID washer.

In our geometry, the effect of an increase in the capacitance is stronger than the effect of a reduction in the SQUID inductance, resulting in a reduction in the frequency of the LC-resonance. At the bias current corresponding to the LC-resonance frequency, the voltage swing even fell to zero. However, in most cases, keeping the insulation thickness at $\sim 1.5 \, \mu\text{m}$ made it possible to avoid the appearance of the LC-resonance in the vicinity of the bias current of the DC SQUID, while providing sufficient inductive coupling between the input coil of the FT and the washer of the DC SQUID. For optimum insulation thickness the estimated coupling coefficient between the input coil of the FT and the SQUID washer was about $\alpha = \sqrt{2(1-L_{\text{Seff}}/L_S)} = 0.87$. A further decrease in the SQUID inductance $L_S$ and a simultaneous decrease in the insulator thickness will ensure an unchanged resonance frequency.

![Figure 5. Noise spectrum of the type A magnetometer.](image)

The type A magnetometers were operated in an unshielded environment without suppression of either the bias current or the SQUID voltage swing. The white noise of the sensors in the unshielded environment also remained unchanged. The intrinsic magnetic field noise values of the magnetometers were measured in the composite magnetic shield. For the best type A magnetometer, the field resolution achieved was $\sim 18 \, \text{fT}/\sqrt{\text{Hz}}$ at 77 K. However, the typical field resolution was about twofold worse (see Figure 5). The non-zero flux-creep-induced resistance $\sim 4 \, \text{p}\Omega$ and the corresponding time constant $\sim 10^4 \, \text{sec}$ can explain the low-frequency component in the noise spectrum of the type A
magnetometer shown in Figure 5, assuming a flux-creep-induced resistance of $\sim 10^{-19} \, \Omega \cdot \text{cm}$ in our films compared to the value $6 \times 10^{-18} \, \Omega \cdot \text{cm}$ obtained in [15] for YBCO films prepared by the laser ablation deposition technique. Measurements in smaller than the present 100 nT residual magnetic fields in the composite magnetic shield and improved pinning of the Abrikosov vortices can further reduce this low-frequency noise of the sensors.

Increasing the linear dimensions of the FT pickup loop by $K$ times can further improve the field resolution of the flip-chip sensors in about $K^{3/2}$ times [6]. Once the sensors in the Earth’s magnetic field had been moved or rotated, the sensors had to be heated above the superconductor transition temperature for about 3 minutes to remove magnetic flux that penetrated into the high-$T_c$ films of the SQUID body and to improve the low-frequency noise properties of the sensors. This disadvantage of type A magnetometers can be avoided with type B magnetometers.

2.2. Type B magnetometers

The first prototype of a passive HPF based on integrating a LR-circuit into the superconducting FT was realized in the present work. The aim was to diminish the effect of huge but slowly changing magnetic fields on the SQUID, for example, during movement or rotation in the Earth’s magnetic field. The task was to achieve the time constant $\tau > 1$ sec for the integrated thin film HPF to get sufficient field resolution at frequencies above 100 Hz. To accelerate the dissipation of the low-frequency component of the circulating current, we integrated a low-noise normal metal resistor with a very small resistance in series with the pickup coil and the input coil inductances of the FT. The problem was to achieve such a low-noise resistor with a resistance value just between the values of the flux-creep-induced resistance of superconductors ($< 0.1$ n$\Omega$) and the resistance of commercially available normal conducting resistors ($> 0.1$ m$\Omega$). The normal conducting FTs have a much higher resistance of about 1 $\Omega$ [13].

A sketch of a thin-film resistor with low magnetic noise and an ultra low resistance is shown in Figure 6. We constructed [12] the low ohmic resistor from two 50-µm-wide meander-like superconducting coplanar lines (1) and (2) connected them to each other using a silver film (3). The total length of the lines was about 100 cm and the distance between the lines was about 50 µm. The meander-like resistor should produce relatively low (negligible) magnetic flux noise for outside circuits because due to its structure the magnetic field generated by Nyquist noise in the silver layer is essential only in the vicinity of the coplanar lines.

A 1-µm-thick silver film was deposited ex-situ on a freshly deposited YBCO film. After structuring, the silver film electrically connected the superconducting lines. The estimated resistance of this structure was $R = 1$ µ$\Omega$ at 77 K. This value is the sum of the resistance of the silver film $R_{\text{Ag}} = 0.9$ µ$\Omega$ and the resistance of the contacts between the silver and YBCO films $R_{\text{cont}} = 0.1$ µ$\Omega$. The
estimated specific contact resistivity for the contact between the silver film and YBCO film was \( \rho_c \approx 5 \times 10^{-8} \, \Omega \cdot \text{cm}^2 \). To provide the low contact resistance for the silver film deposited \textit{ex-situ} on YBCO, it is important that the top YBCO film should be fresh. In our case the transfer time between two different sputtering machines was kept below 5 min. This value corresponds to one obtained in [24] for similar \textit{ex-situ} contact between a silver film deposited on a fresh YBCO film. To avoid possible deoxygenating of the YBCO surface at the interface to silver we first sputtered 30 nm of silver in the 30 % oxygen and 70 % argon gas mixture. The rest of the silver was deposited in pure (99.999 %) argon. A dc-magnetron sputtering technique was used to deposit the silver film.

To provide a dissipation time constant \( \tau = \frac{L}{R} \approx 10 \, \text{sec} \) with a resistance \( R \approx 1 \, \mu\Omega \) it is necessary that the inductance of the FT is \( L = 10 \, \mu\text{H} \). For example, the standard high-\( T_c \) magnetometer HTM-16 has a pickup loop of 16 mm [6] and an inductance of \(~70 \, \text{nH}\). The size of the pickup coil of the FT is limited by the size of the substrate washer and the only possibility of increasing the inductance \( L \) was to use ten turns for the pickup coil instead of one turn.

For the type B magnetometers we constructed a special FT with 10 turns in a pickup coil measuring 16 mm x 16 mm with a serially connected meander-formed 1-\( \mu\Omega \) thin-film silver resistor. A photo of this type of FT is shown in Figure 7. The FT had two epitaxial YBCO layers for the coils and their return lines. An epitaxial PBCO/STO multilayer film was used for the insulation between the superconducting layers. Once the top YBCO layer had been deposited, the structure was oxidized at 500 °C for 1 hour and cooled down to room temperature at a rate \( \sim -10 \, \text{deg/min} \). The operation temperature of the FT and the whole magnetometer was 77 K.

Figure 7. Photo of the 16 mm x 16 mm multilayer FT with integrated HPF intended for type B magnetometers.

Preliminary tests were performed on the flux transformers simply by turning them in the Earth’s magnetic field under a high-\( T_c \) DC SQUID gradiometer system [25]. While for the FT in the type A magnetometers, the gradiometer signal changed from one constant level to another, in the case of the FT in the type B magnetometers, it always relaxed to a value of zero in a few seconds. This simple experiment demonstrated the achievement of a dissipation time constant of \( \tau \approx 7 \, \text{sec} \) for the integrated HPF due to a resistance of \( \sim 1 \, \mu\Omega \) of the silver resistor.

The FT with the HPF was inductively coupled to a \(~130\)-pH DC SQUID, which had an effective inductance of \(~80\) pH after the flip-chip arrangement because part of the SQUID hole was screened by the return line of the FT input coil. The estimated coupling coefficient of the SQUID and the input coil of the FT was \( \alpha = 0.88 \). The DC SQUID hole and washer of the type B magnetometers can be classified as the type “A” washer in Figure 11 in [19]. The flux sensitivity of the type A magnetometer
was $-2.6 \text{nT}/\Phi_0$, while the flux sensitivity of the screened DC SQUID itself was $-40 \text{nT}/\Phi_0$. Voltage swings in the type B SQUID magnetometers were observed up to about 20 $\mu$V peak to peak.

The relatively large DC SQUID inductance was required to provide sufficient direct inductive coupling between the feedback coil and the SQUID. If the feedback coil was coupled to the SQUID mediated by the FT, as it was done for type A magnetometers, the bias flux, for example, could not be set at operation point $\Phi_0/4$ because any bias flux induced in the input coil would relax within the FT to zero in few seconds. As a result, closing the feedback would bring the system in saturation, thus making measurements impossible. A 50-turn Cu-wire feedback coil was placed on the back side of the SQUID’s substrate at a distance of $\sim 2$ mm from the SQUID’s washer. Due to the relatively small size of the SQUID washer and the relatively large separation the mutual inductance between the feedback coil and the screened SQUID was only $\sim (10 \mu A/\Phi_0)^{-1} = 200 \text{pH}$ and the estimated coupling coefficient only $-0.2$.

Nevertheless it was possible to operate the type B flip-chip magnetometers in the closed flux-lock-loop mode. The cut-off frequency of the HPF $f_0 = R/2\pi L$ and the corresponding dissipation time constant in the FT of $\tau = 7$ sec were confirmed by measurements in low-frequency magnetic fields generated by a signal generator. The sensor was placed inside a five-turn coil with a diameter of 15 cm, which in turn was placed inside a cylindrical $\mu$-metal magnetic shield with a diameter of 50 cm.

Stable operation of type B magnetometers was demonstrated outside the magnetic shield. Neither the slow movement (time constant $> 10$ sec) of the sensor together with the cryostat nor the changing of the background magnetic field by magnet movement near the sensor unlocked the feedback of the measurement system or increased its intrinsic noise. Faster movements (time constant $< 1$ sec) in the Earth’s magnetic field unlocked the measurement system due to weak coupling of the feedback coil to the SQUID in this prototype sensor configuration. At low frequencies, the system operation frequency bandwidth was, limited by the cut-off frequency of the HPF, while at high frequencies, it was limited to about 200 Hz by the gain of the feedback circuit. A larger voltage swing and improved coupling of the feedback coil to the SQUID can potentially significantly increase the upper cut-off frequency and thus significantly increase the bandwidth of the measurement system.

![Figure 8](image.png)

**Figure 8.** Measured and calculated field resolution for type B magnetometers with HPF containing a 1-$\mu$A silver resistor and a total FT inductance of 7 $\mu$H. The drop above $\sim 200$ Hz is an artifact due to the limited gain of feedback electronics.
The measured and calculated field resolution for type B magnetometers with HPF, with a 1-µΩ silver resistor and an FT total inductance of 7 µH are shown in Figure 8. AC-bias electronics was used for the measurements. The observed field resolution of the type B magnetometers fits the expected intrinsic low-frequency noise of the magnetometer caused by Nyquist noise in the HPF at frequencies below about 10 Hz. However, the white noise level is still about five times higher than the expected value of about 40 fT/√Hz. There are several possible reasons for this elevated white noise: normal conducting micro-shorts in the multilayer FTs; the use of still non-optimized SQUID layout and flip-chip coupling for the current type B magnetometers as well as possible emission of the magnetic white noise by the ultra-low-ohmic resistor of the HPF. Further study is required to identify and suppress the sources of the excess noise.

3. Discussion

The two types of the flip-chip high-Tc DC SQUID magnetometers realized are interesting test objects for analysing physical effects that contribute to their intrinsic noise. This analysis can be used to further improve the operation parameters of these DC SQUIDs. The main sources of the intrinsic flux noise of the SQUID sensors are the Nyquist noise of the Josephson junctions, thermally activated hopping of Abrikosov vortices, noise from the resistors and defects in the FT, as well as the parasitic effects caused by the strong coupling between the FT and the SQUID. The voltage noise of the preamplifier $S_{1/2}$ is typically about 0.3 nV/√Hz and is usually small compared to the total intrinsic noise of the high-Tc SQUID sensor.

The thermally activated hopping of the Abrikosov vortices between the pinning sites depends on the current due to the current-dependent pinning energy. Hence, even if the circulating current is much less than the critical current, the hopping of the Abrikosov vortices in the superconductor generates a voltage, which opposes to the current. This leads to a flux-creep-induced effective resistance of the high-Tc superconductor films and to the low-frequency flux noise in the FT and in the SQUID [15]. Improving the quality of the high-Tc films, conducting the measurements in a smaller residual magnetic field of the magnetic shield, and improved pinning of the Abrikosov vortices (as done e.g. in [26]) can further reduce the low-frequency noise of the sensors.

The white noise of the SQUIDs is determined mainly by the thermal fluctuations in the Josephson junctions:

$$S_{1/2} = S_{1/2}^{\text{J}} = \left[ \frac{12k_B T}{R_N} \left( \frac{R_s}{2} + \frac{L_s^2}{4} \left( \frac{\partial V}{\partial \Phi} \right)^2 \right) \right]^{1/2} + S_{Ve}$$

(1)

where it was assumed that the dynamic resistance of the DC SQUID $R_{\text{dyn}}$ at the operation point $R_{\text{dyn}} = R_{\text{dyn}}/2 = R_N/2$, where $R_{\text{dyn}}$ is the dynamic resistance and $R_N$ is the normal resistance of one Josephson junction in the DC SQUID [23] and the maximum transfer function of the DC SQUID is determined by the expression [27]:

$$\frac{\partial V}{\partial \Phi} \approx \frac{4}{\Phi_0} \cdot \frac{I_C R_N}{1 + \frac{2 I_C L_S}{\Phi_0}} \cdot \exp\left(-3.5 \pi^2 \frac{k_B T L_s}{\Phi_0^2}\right)$$

(2)

The SQUID voltage swing $\delta V_{pp}$ is equal to $(\partial V/\partial \Phi)\Phi_0/\pi$ in the limit of the sinusoidal voltage modulation with applied magnetic flux $V(\Phi)$. 

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The white flux noise of an autonomous SQUID was estimated for typical operation parameters of the SQUID according to expression (1) and is shown in Figure 9. The calculated value \(-3 \mu \Phi_0/\sqrt{Hz}\) fit well to the measured white noise level \(-4 \mu \Phi_0/\sqrt{Hz}\) observed for the noise spectrum of an autonomous DC SQUID with an inductance \(-40 \text{ pH}\), as shown in Figure 4.

![Figure 9. Theoretical estimation of the white flux noise of an autonomous DC SQUID compared with the measured flux noise of the 40-pH DC SQUID for type A magnetometer (■) and the flux noise of the 130-pH DC SQUID for the type B magnetometer (▲).](image)

Typically, the Stewart-McCumber parameter \(\beta_C\) of the high-\(T_c\) bicrystal Josephson junctions is less than 0.5 at 77 K. This value is low enough that the suppression of the SQUID voltage swing due to the parameter \(\beta_C\) can be neglected [8]. At \(\beta_L = 2L_S I_c/\Phi_0 = 1\) the SQUID bias voltage \(V = I_c R_N (2/\pi \beta_c)\), corresponding to the LC-resonance in the SQUID loop at this capacitance, exceeds the characteristic voltage \(V_c = I_c R_N\). Therefore, this LC-resonance does not degrade the SQUID voltage swing.

The tight coupling of the FT to the SQUID introduces additional noise due to resonances in the FT and shifts the LC-resonance of the SQUID. For the pure STO insulation between the superconducting layers in the multilayer FT kinks-like resonance structure was observed in the \(V(\Phi)\) characteristics of the magnetometers (see e.g. [28] and references therein). The addition of a resistive PBCO layer in the insulation has allowed to suppress these kinks in the \(V(\Phi)\) characteristics of the magnetometers. An optimization of the distance between FT and the SQUID kept the SQUID’s LC-resonance voltage above \(V_c\).

As long as there is no significant degradation of the coupling coefficient “\(\alpha\)”, reducing the SQUID inductance \(L_s\) should improve the field resolution of the inductively coupled magnetometers [29]:

\[
B_N = \left(\frac{\partial B}{\partial \Phi}\right) S_{\phi}^{1/2} = \frac{L_p + L_i}{\alpha \sigma \sqrt{L_i L_s}} S_{\phi}^{1/2} = \frac{1}{\alpha} \sqrt{\frac{L_i}{R_n}},
\]

whereas for the type A flip-chip high-\(T_c\) DC SQUID magnetometers the inductance of the pick-up loop \(L_p \sim 40 \text{ nH}\) is equal to the inductance of the input coil \(L_i\) and the area of the pick-up loop \(\sigma\)
Our experience shows that reducing SQUID inductance down to at least 40 pH does not degrade the field resolution, but rather significantly improves the voltage swing and operational stability of the DC SQUID magnetometers in the magnetically unshielded environment.

A large change in the magnetic field component, which is normal to the pickup loop of the 8-mm FT, for example, due to movement or rotation of the magnetometers in the Earth’s magnetic field, leads to an induction of about 30 times stronger magnetic field at the SQUID, approaching in the worst case a magnetic field of about 1 mT. The magnetic field $B > 100 \mu T$ penetrates into the SQUID washer creating Abrikosov vortices and suppresses the critical current $I_c(B)$ of the bicrystal Josephson junctions due to the “Fraunhofer pattern” dependence $I_c(B)$. Part of the magnetic field amplified by the FT can reach the Josephson junctions suppressing their critical currents and the voltage swing of the DC SQUID. Then the only possibility of recovering SQUID operation is to reduce the induced circulating superconducting current in the FT. For type A magnetometers, the standard procedure for removing the nonequilibrium part of the frozen magnetic flux from the SQUID washer and dissipating the induced circulating superconducting current in the FT is to heat the magnetometer above the superconducting transition temperature using an integrated nonmagnetic heater. This procedure together with subsequent cooling to the operation temperature usually takes up to about 5 minutes, which can be inconvenient for some applications.

Until now, the only alternatives to heating the magnetometer were the application of passive or active modifications of the flux dam [9, 10] or local compensation of the Earth’s field [11]. Our suggestion was to solve this problem automatically in the FT before the high magnetic fields reach the DC SQUID by integrating the passive HPF into the FT [12]. This method also has its disadvantages. In the following part of the paper we will discuss the features and possible application areas of SQUID sensors with superconducting FTs containing a passive HPF based on the ultra-low-resistance thin-film resistor integrated in series with the coils of the FT.

A meander-like coplanar line structure of the ultra low resistance thin film resistor (see Figure 6) was chosen because it generates negligibly small magnetic field noise. The structures wherein, e.g., the thin film electrodes are interlocked with each other such that one set of “fingers” of the first electrode are located in the gaps between another set of “fingers” of the second electrode (interdigitated comb-shaped electrodes) can achieve lower resistance values, but they demonstrate a large magnetic field noise because they contain normal conducting loops having an area comparable with the area of the pickup loop of the FT. Large normal conducting soldered contacts of high-$T_c$ wires like it was used in reference [14] would also generate significant magnetic noise penetrating between the high-$T_c$ filaments of the superconducting electrodes. A possible low-noise alternative to the present meander-like coplanar line resistor can be a planar three-layer structure containing continuous superconducting electrodes and a normal conducting interlayer. Such planar three-layer structures can be produced with low-$T_c$ superconducting electrodes in the form of thin films or foils as well as with the high-$T_c$ superconducting electrodes in the form of thin epitaxial films deposited on different substrates and electrically connected to each other in a flip-chip configuration via the low ohmic, e.g., silver interlayer.

The resistor (see Figure 2) having the ultra low resistance $R$ generates the following Nyquist noise current in the frequency bandwidth $\Delta f$ and the total inductance $L$ of the FT:

$$
\langle I_N \rangle^2 = \frac{4k_B T R \Delta f}{R^2 + (2\pi f)^2}.
$$

This noise current in the FT creates magnetic field noise in the input coil of the FT and thus leads to additional low-frequency flux noise in the DC SQUID:
which, in turn, leads to a low-frequency noise contribution to the intrinsic noise of the magnetometer, limiting its magnetic field resolution at low frequencies:

\[
\frac{1}{2} S^2 = \alpha \sqrt{L_r L_s \langle I \rangle} = \alpha \frac{4k_B TR L_s \Delta f}{R^2 + (2\pi f)^2}
\]

where \( m = 10 \) is the number of turns in the pickup coil and \( \sigma = 2.56 \text{ cm}^2 \) is the area of one loop of the pickup coil of the FT.

Taking into account the calculated white flux noise of the magnetometers (see equation (1)) we estimated the total field resolution of the magnetometers with the current prototype FT containing the passive HPF (see Figure 10).

**Figure 10.** Calculated field resolutions for the type B magnetometers with total inductance of the FT of 7 \( \mu \text{H} \) at 77.4 K and 4.2 K.

Two main disadvantages of the present type B magnetometers were observed: high low-frequency noise and weak coupling of the feedback coil. To reduce the low-frequency noise down to about 100 fT/\( \sqrt{\text{Hz}} \) at 77 K, to the level of the type A magnetometers, an increase in the dissipation time constant \( \tau \) to more than about 2.5 hours is required. This is impractical, but would be possible if the resistance of the integrated resistor was reduced and the inductance increased both about thirtyfold to 30 n\( \Omega \) and 210 \( \mu \text{H} \), respectively. The increase in the size of the pickup loop and/or use of low-T\( \text{c} \) SQUID magnetometers with the coils wound from a superconducting wire would make it easier to increase the dissipation time constant.

The coupling of the SQUID and the feedback coil can be improved, for example, by increasing the size of the SQUID washer, introducing a directly coupled flux antenna on the SQUID chip or using an intermediate FT. In all cases the SQUID itself will be more sensitive to the external fields and suffer from large changes of the background fields. Shielding of the SQUID from the background fields (not FT!) is desirable and is also easier to realize with low-T\( \text{c} \) sensors.
Figure 11 shows possible applications of the low ohmic resistors as a dissipative element in the pickup coils of the directly coupled SQUID magnetometer (Figure 11a) and SQUID gradiometers of first order (Figure 11b-d) and second order (Figure 11e). In all pictures (1) denotes the pickup coil, (2) – the low ohmic resistor, and (3) – the input coil. The arrows indicate the direction of the induced currents in separated coils by similar changes of the external magnetic fields. The input coil of the directly coupled magnetometer is part of the SQUID loop (Figure 11a).

![Figure 11](image)

**Figure 11.** Additional examples of possible superconducting FTs with an integrated HPF: (a) directly coupled SQUID magnetometer and (b-d) SQUID gradiometers of first order and (e) SQUID gradiometers of second order.

In the cases of the gradiometers shown in Figure 11b and Figure 11c, the spatially homogeneous changes of the external magnetic field only generate the current in the perimeter loop of the gradiometer but no residual current flowing through the input coil. In the cases of the gradiometers shown in Figure 11d and Figure 11e, the spatially homogeneous changes in the external magnetic field cause the currents to cancel each other and no net current flows in the pickup coils and through the input coil. The resistors help to dissipate currents produced by the slowly changing spatially inhomogeneous background magnetic fields.

Further optimization of type B magnetometers would open the possibilities for their applications in, for example, non-destructive evaluation, geomagnetic exploration and biomagnetic measurements.

4. Summary

We realized and investigated DC SQUID magnetometers with different high-$T_c$ superconducting FTs: for the type A magnetometer the FT contained a single-turn pickup coil and a multilayer input coil while for the type B magnetometer the FT contained an integrated passive HPF with an ultra-low-ohmic resistor placed in series with the multilayer coils. The resonances in FT were damped by the PBCO film in the PBCO/STO-heterostructural insulator layer between the superconducting films. Shifting was observed of the LC-resonance in the DC SQUID caused by parasitic capacitance between the SQUID and the FT. An optimization was performed of the separation distance between the FT and the SQUID to avoid suppression of the SQUID voltage swings and corresponding increase of the SQUID flux noise. An experimental and theoretical analysis was performed of the intrinsic noise of the high-$T_c$ DC SQUID with a superconducting flux transformer (FT) containing resistive elements. Agreement was obtained between the calculated and measured values.

We realized a low-noise ultra-low-ohmic resistor with resistance values between the flux-creep-induced resistances of the superconductors (below 0.1 nΩ) and resistances of conventional resistors...
We developed an HPF with time constant ~7 sec based on an RL-circuit integrated in the high-T$_c$ superconducting FT with such ultra-low-ohmic resistor having the resistance ~1 µΩ and inductance of a 16-mm pickup coil ~7 µH. Both coils of the FT with HPF were multiturn multilayer high-T$_c$ superconducting coils with resonance damping by the PBCO film in the PBCO/STO-heterostructural insulator layer between the superconducting films. Contribution of the integrated HPF to the intrinsic noise of the high-T$_c$ DC SQUID sensors was compared with calculated values.

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6. References
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