Low noise $YBa_2Cu_3O_{7-x}$ SQUID magnetometers operated with additional positive feedback

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Three magnetometers based on dc superconducting quantum interference devices (SQUIDs) fabricated from $YBa_2Cu_3O_{7-x}$ have been operated in a magnetically shielded room using a flux-locked loop involving additional positive feedback with bias current reversal. Two of these devices, integrated multiloop dc SQUIDs with outer diameters of 7 mm, achieved white noise levels of 10 $fT/\sqrt{Hz}$ for bicrystal junctions and 30 $fT/\sqrt{Hz}$ for step-edge junctions. The third magnetometer involved a flux transformer with a 10×10 mm^2 pickup coil connected to a 16-turn input coil which was inductively coupled to a bicrystal SQUID. This device achieved a white noise of 16.2 $fT/\sqrt{Hz}$. High quality magnetocardiograms were obtained without signal averaging. © *1996 American Institute of Physics.* [S0003-6951(96)02013-8]

To operate a dc superconducting quantum interference device (SQUID) in a flux-locked loop one commonly applies an oscillating magnetic flux and demodulates the voltage across it.[1] An alternative scheme, additional positive feedback (AFP),[2] involves no such modulation, enabling one to construct lower cost and more compact multichannel systems. This scheme has been used successfully in several multichannel systems involving low-transition temperature (T_c) SQUIDs. The lack of modulation in the original APF scheme means that low-frequency critical current or resistance fluctuations in the Josephson junctions[3] are not suppressed; however, in high quality low-T_c junctions the influence of these fluctuations is often negligible compared with other sources of low-frequency noise. In contrast, critical current fluctuations are the dominant source of low-frequency noise in high-T_c dc SQUIDs and one must inevitably use a bias current reversal scheme to reduce them.[3] Recently, an APF scheme with bias reversal has been developed and successfully tested with low-T_c multiloop SQUIDs.[4] In this letter, we report the use of bias reversal in an APF flux-locked loop to reduce the low-frequency noise in high-T_c SQUID magnetometers, and demonstrate the use of these devices to obtain high quality magnetocardiograms in a magnetically shielded room.

For this study, we used two integrated multiloop magnetometers and one flip-chip magnetometer. The multiloop magnetometers have an outer diameter of 7 mm and consist of 16 pickup loops connected in parallel across two junctions to form a SQUID with an inductance L of about 145 pH.[5,6] One of these devices was fabricated at Philips Hamburg using a $YBa_2Cu_3O_{7-x}$–$SrTiO_3$–$YBa_2Cu_3O_{7-x}$ (YBCO–STO–YBCO) multilayer process with step-edge junctions.[7] The other multiloop device and the flip-chip magnetometer were fabricated at the University of California, Berkeley and Lawrence Berkeley National Laboratory using a YBCO–STO–YBCO multilayer process with bicrystal junctions.[8] The flip-chip magnetometer consists of a flux transformer with a 10×10 mm^2 pickup loop connected to a 16-turn input coil that is inductively coupled to a 500 μm square washer SQUID with bicrystal junctions.[8,9] The flux transformer and SQUID are pressed together with a 3-μm-thick mylar foil between them. The crossover was aligned to cover about 75% of the length of the slit in the SQUID washer (type A/C in Ref. 9), thus providing a ground plane to reduce the self-inductance of the SQUID to about 30 pH. The parameters of the magnetometers are listed in Table I.

The APF circuit consists of a resistor R_a and a coil L_a in series, connected in parallel with the SQUID (Fig. 1). A constant bias current I_b maintains a voltage V across the SQUID which is equal to the bias voltage V_b if the SQUID is at its working point. A small increase in the magnetic flux Φ in the SQUID produces a small change in V. The resulting current change in the APF circuit induces an additional flux in the SQUID via the mutual inductance M_a between the APF coil and the SQUID, thereby increasing the flux-to-voltage transfer function to $V_\Phi=\partial V/\partial\Phi=V_{\Phi,i}/(1-G_a)$, where $V_{\Phi,i}$ is the intrinsic transfer function without APF (i.e., with $R_a\rightarrow\infty$) and

$$G_a=(M_a+\partial\Phi/\partial I)V_{\Phi,i}/R_a\lesssim1 \quad (1)$$

is the APF gain.[10] Note that with APF the bias current must be increased by $\Delta I_b=V_b/R_a$ compared to the case without APF in order to have identical working points. The spectral density of the total flux noise with APF at frequency f is given by[10]

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TABLE I. Parameters and performance of high-T_c magnetometers with additional positive feedback operated inside a magnetically shielded room. The noise was measured with bias reversal (values in parentheses with static bias).

Magnetometer type	Flip-chip	Multiloop	Multiloop	
Junction technology	bicrystal	bicrystal	step-edge	
Pickup coil shape	square	circular	circular	
Pickup coil size D_p	10	7	7	mm
Sensitivity B/Φ	2.7	1.24	1.23	nT/Φ_0
SQUID inductance L	$\simeq 30$	$\simeq 145$	$\simeq 145$	pH
Mutual inductance M_a	330	840	1050	pH
APF resistance R_a	12	34	8.7	Ω
Junction resistance R	1.8	13	3	Ω
Bias current I_b	186	11	111	μA
Bias voltage V_b	32	24	$\simeq 30$	μV
Voltage swing $2\delta V$	21.5	17.5	4.7	μV
$V_\Phi = \partial V/\partial\Phi$	$\simeq 900$	$\simeq 700$	$\simeq 125$	$\mu\mathrm{V}/\Phi_0$
$-\partial\Phi/\partial I = R_{\mathrm{dyn}}/V_\Phi$	$\simeq 0.03$	$\cdots$	0.12	$\Phi_0/\mu\mathrm{A}$
$\sqrt{S_{B,i}}$(white) [a]	14.4 (13)	8.8 (7.7)	26 (22.5)	$\mathrm{fT}/\sqrt{\mathrm{Hz}}$
$\sqrt{S_B}$(white)[a]	16.2 (15)	10 (9)	30 (27)	$\mathrm{fT}/\sqrt{\mathrm{Hz}}$
$\sqrt{S_B}$(1 kHz)	16.3 (35)	13 (22)[b]	31 (32)	$\mathrm{fT}/\sqrt{\mathrm{Hz}}$
$\sqrt{S_B}$(100 Hz)	17.8 (91)	53 (74)[b]	34.6 (57)	$\mathrm{fT}/\sqrt{\mathrm{Hz}}$
$\sqrt{S_B}$(1 Hz) [c]	135 (850)	110 (280)	94 (800)	$\mathrm{fT}/\sqrt{\mathrm{Hz}}$

[a] Measured with bias reversal at 5 kHz (with static bias at 20 kHz).

[b] Deteriorated due to a random telegraph signal.

[c] Includes environmental noise contribution of $\simeq 50$ $\mathrm{fT}/\sqrt{\mathrm{Hz}}$.

$$S_\Phi(f) = S_{\Phi,i}(f) + 4k_BTR_a(G_a/V_{\Phi,i})^2 + S_{V,\mathrm{amp}}(f)/V_\Phi^2 + S_{I,\mathrm{amp}}(f)(\partial\Phi/\partial I)^2. \tag{2}$$

Here, $S_{\Phi,i}(f)$ is the intrinsic flux noise spectral density of the SQUID without APF, $4k_BTR_a$ is the Nyquist voltage noise of the APF resistor, $S_{V,\mathrm{amp}}(f)$ and $S_{I,\mathrm{amp}}(f)$ are spectral densities of the voltage and current noise of the preamplifier, $-\partial\Phi/\partial I = R_{\mathrm{dyn}}/V_\Phi$ is the current sensitivity[11] (i.e., current-to-flux transfer function at constant SQUID voltage), and $R_{\mathrm{dyn}} = \partial V/\partial I$ is the dynamic resistance of the SQUID. Equation (2) shows that APF reduces the effects of the preamplifier voltage noise by increasing V_Φ, whereas the effect of the current noise remains unchanged since $-\partial\Phi/\partial I$ is not affected by APF.[11] The bandwidth of the enhanced transfer function, given by the bandwidth of the APF circuit $f_a = R_a/2\pi L_a$ divided by $V_\Phi/V_{\Phi,i}$, is $(1-G_a)R_a/2\pi L_a$. Typically, we choose $G_a \simeq 0.9$ as a good compromise between low noise and high bandwidth.

The SQUID was connected directly to the preamplifier (Analog Devices AD797), which has white voltage and current noise levels of 1 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$ and 2 $\mathrm{pA}/\sqrt{\mathrm{Hz}}$ with $1/f$ noise corner frequencies of about 7 and 270 Hz, respectively. For all the magnetometers we used a 7-turn APF coil ($L_a \simeq 3$ μH) and a single-turn feedback coil of 0.05 mm diam, varnish-insulated Cu wire. The metal film APF resistor was selected for each SQUID to make $G_a \simeq 0.9$. The current noise of the preamplifier is sufficiently low so that it was not necessary to reduce $-\partial\Phi/\partial I$ by bias current feedback (BCF).[11] To minimize the number of wires between 77 K and room temperature we measured the SQUID voltage in a two-terminal configuration. The bias voltage V_b was generated by passing a bias current I_b through a cooled metal film resistor R_V. The deviation between the SQUID and bias voltages was amplified, integrated, and fed back as a current into the feedback coil. For the magnetometers used here, the feedback range was between ±60 and ±90 nT, and the 3 dB bandwidth of the flux-locked loop was between 40 and 200 kHz. The feedback electronics are described in detail elsewhere.[4]

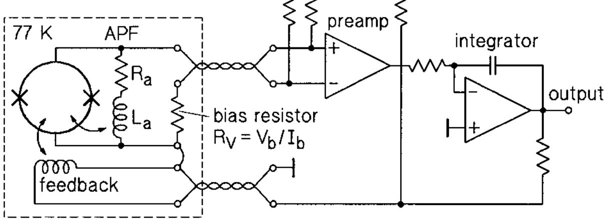

FIG. 1. APF flux-locked loop. The Josephson junctions are indicated by crosses on the SQUID loop.

The SQUID probe was inserted into a low-noise biomagnetic dewar filled with liquid nitrogen, with a separation of about 13 mm between the magnetometer and the outer end of the dewar. The system was operated in the Berlin magnetically shielded room (BMSR).[12] The sensitivity B/Φ (B is the flux density) was measured using a calibrated 20-cm-diam Helmholtz coil. The V-Φ characteristics of the flip-chip and step-edge multiloop magnetometers are shown inset in Fig. 2, along with their magnetic flux density noise measured with both static bias current and bias reversal at 15 kHz (flip-chip) or 9 kHz (multiloop). The basic parameters of the V-Φ characteristics (voltage swing 2 δV and transfer function V_Φ) and the noise at selected frequencies are also listed in Table I. With static bias the APF scheme does not suppress critical current fluctuations of the two junctions that are in phase, so that the low-frequency noise is higher than with the flux modulation scheme,[3] which does suppress these fluctuations. With bias reversal, both in-phase and out-of-phase fluctuations are suppressed,[4] and the low-frequency noise is strongly reduced, as is evident in Fig. 2 for frequencies below a few kHz. We see that at 1 Hz the noise contains a noticeable contribution from the ambient magnetic field noise inside the shielded room. With bias reversal the white noise of the flip-chip, bicrystal multiloop, and step-edge multiloop magnetometers was 16.2, 10, and 30 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$, respectively; in each case with a static bias the white noise was slightly lower. From Eqs. (1) and (2), we estimated that the intrinsic white SQUID noise levels $\sqrt{S_{B,i}}$ are typically 14% lower than the total white noise levels $\sqrt{S_B}$ mainly due to the Nyquist noise of the APF resistor (Table I).

At frequencies between a few Hz and about 1 kHz the noise of the bicrystal multiloop magnetometer was seriously degraded by a random telegraph signal (RTS) with an amplitude of about 9×10^{-3} Φ_0 (Φ_0 is the flux quantum) which could not be removed by repeated thermal cycling. We believe this RTS was caused by a defect that developed in the eight months of storage since the original testing of the device.[6] To determine the noise in the absence of the RTS we measured a noise spectrum from pulse-free time traces using the ‘‘manual preview’’ averaging mode of our HP

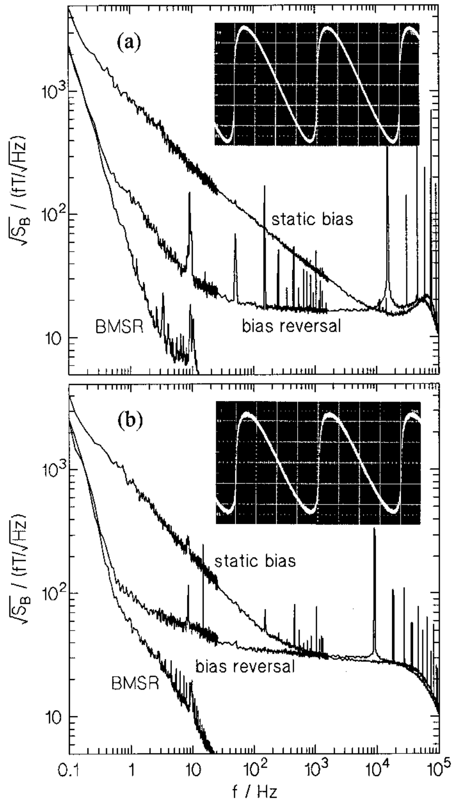

FIG. 2. Noise spectra (a) of the flip-chip magnetometer and (b) of the step-edge multiloop magnetometer measured in the magnetically shielded room. The background noise in the shielded room (curves ''BMSR'') was measured with a low- T_c system at the corresponding positions. The lines in the spectrum are due to mechanical vibrations, power line interference, and bias reversal operation. The insets show the V-Φ characteristics with a horizontal scale of 0.25 Φ_0/div and a vertical scale of (a) 4 μV/div and (b) 1 μV/div.

35665A spectrum analyzer. This selective averaging reduced the noise with bias reversal by a factor of 5 to 10.5 fT/$\sqrt{\text{Hz}}$ at 100 Hz.

To illustrate the low noise achievable with these high-T_c magnetometers operated with APF, in Fig. 3 we show two magnetocardiograms recorded from a healthy male volunteer with the flip-chip magnetometer (a) and step-edge multiloop magnetometer (b). The low noise levels (about 2 and 3 pT peak-to-peak in a 200 Hz bandwidth for the flip-chip and multiloop devices) demonstrate an excellent signal-to-noise ratio in a single-shot cardiogram. The quality of these biomagnetic measurement data demonstrates that high-T_c magnetometers have now reached a noise level that would be adequate for many clinical applications.

In summary, we have used APF to operate high-T_c SQUID magnetometers with low noise and a bandwidth of up to 200 kHz. Two of these magnetometers were used to obtain high quality magnetocardiograms in a magnetically shielded room.

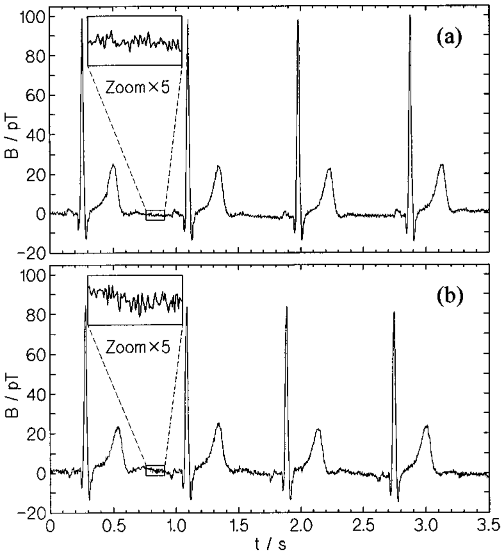

FIG. 3. Real-time trace of a magnetocardiogram measured in the magnetically shielded room without power line filters with (a) the flip-chip magnetometer and (b) the step-edge multiloop magnetometer. The measurement bandwidth is 0.016–200 Hz.

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[1] J. Clarke, W. M. Goubau, and M. B. Ketchen, J. Low Temp. Phys. **25**, 99 (1976).
[2] D. Drung, R. Cantor, M. Peters, H. J. Scheer, and H. Koch, Appl. Phys. Lett. **57**, 406 (1990).
[3] R. H. Koch, J. Clarke, W. M. Goubau, J. M. Martinis, C. M. Pegrum, and D. J. Van Harlingen, J. Low Temp. Phys. **51**, 207 (1983).
[4] D. Drung, Appl. Phys. Lett. **67**, 1474 (1995).
[5] D. Drung, S. Knappe, and H. Koch, J. Appl. Phys. **77**, 4088 (1995).
[6] F. Ludwig, E. Dantsker, R. Kleiner, D. Koelle, J. Clarke, S. Knappe, D. Drung, H. Koch, N. McN. Alford, and T. W. Button, Appl. Phys. Lett. **66**, 1418 (1995).
[7] B. David, D. Grundler, R. Eckart, F. Fanghänel, J. P. Krumme, V. Doormann, and O. Doessel, Supercond. Sci. Technol. **7**, 287 (1994).
[8] F. Ludwig, D. Koelle, E. Dantsker, D. T. Nemeth, A. H. Miklich, J. Clarke, and R. E. Thomson, Appl. Phys. Lett. **66**, 373 (1995).
[9] E. Dantsker, F. Ludwig, R. Kleiner, J. Clarke, M. Teepe, L. P. Lee, N. McN. Alford, and T. Button, Appl. Phys. Lett. **67**, 725 (1995).
[10] D. Drung, in *SQUID Sensors: Fundamentals, Fabrication and Applications, NATO ASI Series*, edited by H. Weinstock (Kluwer, Dordrecht, in press).
[11] D. Drung and H. Koch, IEEE Trans. Appl. Supercond. **AS-3**, 2594 (1993).
[12] S. N. Erné, H.-D. Hahlbohm, H. Scheer, and Z. Trontelj, in *Biomagnetism*, edited by S. N. Erné, H.-D. Hahlbohm, and H. Lübbig (de Gruyter, Berlin, 1981), p. 79.