Integrated High-Transition Temperature SQUID-based Voltmeters Operated at 77 K

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Abstract—The voltage noise levels of high- T_c based $\text{YBa}_2\text{Cu}_3\text{O}_x$ bicrystal SQUIDs and SQUID voltmeters were measured to investigate their noise characteristics. The SQUIDs are of washer type with outer dimension of $90\text{ }\mu\text{m} \times 90\text{ }\mu\text{m}$ and inner dimension of $20\text{ }\mu\text{m} \times 20\text{ }\mu\text{m}$. The SQUIDs have a normal inductance of about 60 pH. The integrated modulation and input coils were circular in shape. The modulation coil has a radius of $r_2 = 80\text{ }\mu\text{m}$ and $r_1 = 60\text{ }\mu\text{m}$ while the input coil for voltage measurement has radius $r_2 = 50\text{ }\mu\text{m}$ and $r_1 = 30\text{ }\mu\text{m}$. Using a dc bias and standard flux locked loop, the spectral density of the voltage noise, S_v , was observed to behave as $1/f$ at low frequencies and the root mean square flux noise, $S_\Phi^{1/2}$, is white and has a value of $\sim 15\text{ }\mu\Phi_0/\text{Hz}^{1/2}$ at 1 kHz. The flux noise levels were reduced to $\sim 4\text{ }\mu\Phi_0/\text{Hz}^{1/2}$ using the ac bias reversing technique. These data suggest that the dominant $1/f$ voltage noise was caused by critical current fluctuations. We further demonstrate that the $1/f$ can be induced by flux motion. The voltage noise levels of the SQUID voltmeters are also reported.

I. INTRODUCTION

The ability of the superconducting quantum interference device (SQUID) to convert an applied magnetic flux to a voltage has been exploited in low transition temperature (T_c) devices to measure not only magnetic field and magnetic field gradient, but also other physical quantities, such as current, magnetic susceptibility, and voltage. In particular SQUID-based voltmeters have proved valuable in measuring tiny voltages [1]. Thus it is natural to consider the design of high- T_c SQUID-based voltmeters and investigate their voltage noise. There are two approaches for designing SQUID voltmeters. First, the flux-nulling method and secondly, the current-nulling method [2]. The paper is aimed at characterization of the voltage noise of SQUID voltmeters, which are operated via the flux-nulling scheme.

II. EXPERIMENTS

The voltage noise levels of SQUIDs were measured using a commonly used flux-locked loop with both dc bias and ac bias reversal techniques [3] with SQUID electronics (NKT SQUID catcher). The noise of the preamplifier in the flux locked mode was $1 \sim 4 \times 10^{-6}\text{ }\mu\Phi_0/\text{Hz}^{1/2}$. The voltage noise

spectral density, S_v , is analyzed with a spectral analyzer (Stanford Research Systems, model FFT 760). The SQUIDs were shielded with two layers of Mu-metal and a high- T_c superconducting $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_y$ cylinder.

The SQUIDs investigated here were bicrystal SQUIDs. The SQUIDs were of square washer type and have an outer dimension of $90 \times 90\text{ }\mu\text{m}^2$ and inner dimension of $20 \times 20\text{ }\mu\text{m}^2$. The self-inductance of SQUIDs was 60 pH calculated from the peak-to-peak value of the $V-\Phi$ curve. To design SQUID voltmeters, we employed the integrated modulation and external coils. The geometry of the integrated modulation and input coils is shown in Fig. 1a. The mutual inductance M between the modulation coil and the SQUID is 43 pH while the mutual inductance M_2 between the input coil and the SQUID is 35.4 pH. The SQUID voltmeter was operated in the flux-nulling mode. The equivalent circuit diagram of voltmeter in the flux-nulling configuration is shown in Fig. 1b.

Fig. 1. Configuration of the integrated SQUID voltmeters. (a) The modulation coil has a radius of $r_2 = 80\text{ }\mu\text{m}$ and $r_1 = 60\text{ }\mu\text{m}$ while the input coil used for voltage measurement has radius $r_2 = 50\text{ }\mu\text{m}$ and $r_1 = 30\text{ }\mu\text{m}$. The modulation and input coils lie on the top of the SQUID washer. (b) Equivalent circuit of measuring voltage V_{RS} . $\Delta\Phi$ is the flux coupled to the SQUID caused by I_{RL} .

Manuscript received September 15, 1998.

This work was supported by the National Science Council of R.O.C. under Grants NSC 87-2112-M002-002 and NSC87-2112-M003-001.

III. RESULTS AND DISCUSSION

In Fig. 2 we show the I-V curves of a bicrystal SQUID at 77.5 K. The I-V curve shows RSJ behavior. The critical current was about 7.7 μ A and the normal state resistance was 8.7 Ω . The peak to peak voltage of the V- Φ curve under optimum bias current is about 20 μ V.

In Fig. 3 we show the root mean square flux noise spectrum, $S_{\Phi}^{1/2}$ of the SQUID using a commonly used dc bias and flux-locked scheme. The flux spectral density, S_{Φ} , is calculated from $S_{\Phi} = S_v / (dV/d\Phi)^2$, where S_v is the voltage noise and $dV/d\Phi$ is the flux to voltage transfer function. The measured root mean square flux noise, $S_{\Phi}^{1/2}$, for the SQUID at 1 kHz was $\sim 15 \mu\Phi_0/\text{Hz}^{1/2}$. When measuring the noise spectrum, the SQUID is biased near I_c so that $dV/d\Phi$ is at its maximum. The noise level at 1 Hz was $\sim 5 \times 10^{-5} \Phi_0/\text{Hz}^{1/2}$ whereas the white noise was $\sim 1.6 \times 10^{-5} \Phi_0/\text{Hz}^{1/2}$ at 1 KHz. The S_{Φ} of the SQUID in the low frequency range (1 Hz $< f < 20$ Hz) showed 1/f behavior. Using the ac bias reversal scheme, we obtained the flux noise as shown in the bottom curve of Fig. 3. One can see that the $S_{\Phi}^{1/2}$ can be reduced by the ac bias reversing scheme. The $S_{\Phi}^{1/2}$ has a white noise level of $6.7 \times 10^{-6} \Phi_0/\text{Hz}^{1/2}$ at 1 kHz. Furthermore, the $S_{\Phi}^{1/2}$ at 1 Hz is reduced to about $1 \times 10^{-5} \Phi_0/\text{Hz}^{1/2}$.

The noise of dc SQUIDs can be classified as the low frequency 1/f noise and the high frequency white noise. At least two separate sources of the 1/f noise have been identified, critical current fluctuations and the motion of magnetic flux. The critical current fluctuation was reduced by the ac bias reversing method. Assuming that the dc SQUID has two symmetrical junctions and if the low-frequency noise arises from critical current fluctuations of the Josephson junction, then the SQUID voltage noise can be expressed as [4]-[6]

$$S_v = (1/2)[(V - IR_d)^2 + (LI_c V_{\Phi})^2] (S_{I_c}/I_c^2) \quad (1)$$

Here, R_d is the dynamic resistance of the SQUID, V is the voltage across the SQUID at the bias current I , $V_{\Phi} = dV/d\Phi$ and S_{I_c} represents the power spectrum of the critical current fluctuations. The first term represents the "in phase" voltage noise across the Josephson element of resistance R_d , and the second term originates from the "out of phase" critical current fluctuation leading to flux noise due to the circulating current. Operating the SQUIDs in the commonly used flux-locked loop mode results in suppression of the "in phase" contribution. An additional bias current reverse mode made the SQUIDs even insensitive to the "out of phase" noise contribution, while the remaining is sensitive to the apparent flux noise and external applied magnetic fields. We note that the $S_{\Phi}^{1/2}$ can be reduced by the ac bias reversing scheme in Fig. 3. These data suggest that the dominant 1/f voltage noise of this SQUID is due to the critical current fluctuations.

To find the S_{I_c}/I_c^2 in equation (1) as a function of the bias current at 77.5 K under zero magnetic field, the flux noise

Fig. 2. I-V and dV/dI curves of a YBCO bicrystal SQUID at 77.5 K under zero magnetic field. The I-V curve shows RSJ behavior. The normal state resistance was 8.7 Ω .

spectra were measured under various dc bias current by using a flux-lock loop scheme. Since the low frequency noise is dominated by the out-of-phase critical current fluctuation, hence the S_{I_c}/I_c^2 can be obtained via the equation $S_{I_c}/I_c^2 = 2S_{\Phi}/(LI_c)^2$ with $L = 60$ pH and $I_c = 7.7 \mu$ A at 77.5 K. Fig. 4 shows the relationship between S_{I_c}/I_c^2 at 6 Hz and the bias current I . It was found that S_{I_c}/I_c^2 decreases with increasing I and reaches to its minimum at $I \sim 6 \mu$ A. Then, the S_{I_c}/I_c^2 turns to become larger as I keeps increasing. Generally speaking, the order of the magnitude of S_{I_c}/I_c^2 at 6 Hz is 10^{-8} Hz^{-1} .

To investigate the effects of external flux on the 1/f noise and demonstrate that the flux motion can indeed induce the

Fig. 3. Noise spectra of the SQUID of Fig. 2. The flux noise of this SQUID under dc bias at 1 kHz was $S_{\Phi}^{1/2} \sim 15 \mu\Phi_0/\text{Hz}^{1/2}$. The flux noise of the SQUID at low frequency range 1 Hz $< f < 20$ Hz shows 1/ $f^{0.5}$ behavior. The line below 20 Hz labeled $f^{0.5}$ demonstrates this. The effect of using bias reversal is shown in lower (dashed) curve.

Fig. 4. S_ϕ/I_c^2 versus I at 6 Hz under zero magnetic field at 77.5 K.

$1/f$ noise, we measured the $S_\phi^{1/2}$ under applied flux Φ using the ac bias reversal mode. Fig. 5 shows flux noise spectra, $S_\phi^{1/2}$, of the SQUID under applied magnetic flux $\Phi = 0.35 \Phi_0$, $0.4 \Phi_0$, $0.425 \Phi_0$, $0.45 \Phi_0$, and $0.5 \Phi_0$ at 77.5 K using the ac bias reversal technique. The bias current of the SQUID is near the critical current where $dV/d\Phi$ is at its maximum. The $S_\phi^{1/2}$ was white when the applied flux is below $0.35 \Phi_0$ and the $S_\phi^{1/2}$ is increased when the applied flux is increased above $0.4 \Phi_0$. The S_ϕ shows $1/f$ behavior in the low frequency range ($1 \text{ Hz} < f < 60 \text{ Hz}$). We noted that the S_ϕ at low frequency range ($1 \text{ Hz} < f < 40 \text{ Hz}$) remains as $1/f$ behavior when the applied flux goes beyond $\Phi = 0.55 \Phi_0$. This can further be seen if we redraw the data of Fig. 5 at $\Phi = 0.35 \Phi_0$, $0.5 \Phi_0$ and $\Phi = 1.35 \Phi_0$ as shown in Fig. 6. Since

Fig. 5. $S_\phi^{1/2}$ of SQUID a under applied magnetic flux $\Phi = 0.35 \Phi_0$, $0.4 \Phi_0$, $0.425 \Phi_0$, $0.45 \Phi_0$, and $0.5 \Phi_0$.

Fig. 6. The $S_\phi^{1/2}$ at applied flux $\Phi = 0.35 \Phi_0$, $0.5 \Phi_0$ and $\Phi = 1.35 \Phi_0$.

SQUIDs are sensitive only to flux motion under the ac bias reversal technique, therefore the $1/f$ voltage noise under applied flux is mainly due to the flux motion. Hence, we have directly demonstrated that the motion of magnetic flux induces the $1/f$ noise in the SQUID. Fig. 6 also shows that the white noise may also be increased by the flux motion.

Fig. 7 shows the $S_\phi^{1/2}$ as a function of applied flux, Φ . At low applied flux ($\Phi < 0.37 \Phi_0$), the $S_\phi^{1/2}$ was a constant value. However, when the applied magnetic flux is larger than $0.37 \Phi_0$, which corresponds to an applied magnetic field of $\sim 7 \text{ mG}$, the $S_\phi^{1/2}$ gradually increased and finally reached a plateau when $\Phi > 0.5 \Phi_0$. We attribute the increased $S_\phi^{1/2}$ to the thermally activated motion of flux vortices in the SQUID washer.

Fig. 7. The $S_\phi^{1/2}$ as a function of applied flux at 6, 100, and 1000 Hz.

Fig. 8. The spectral flux density $S_\Phi^{1/2}$ of the SQUID voltmeter as a function of frequency when $V_{RS} = 0$ and $V_{RS} = 45 \mu\text{V}$.

To utilize the SQUID as a voltmeter, we used the ac bias reversal flux nulling scheme with resistors $R_s = 0.235 \Omega$ and $R_o = 10 \Omega$ (see Fig. 1b). The voltage noise of voltmeters under flux nulling is shown in Fig. 8. Utilizing the formula $S_v^{1/2} \sim S_\Phi^{1/2}(R_o/M_2)$, we obtained a voltage noise of $\sim 0.04 \mu\text{V}/\text{Hz}^{1/2}$ at 3 Hz with $V_{RS} \sim 0$. The voltage noise increases to $0.1 \mu\text{V}/\text{Hz}^{1/2}$ at 3 Hz and shows $1/f$ behavior indicated by the straight line in Fig. 7 when the input voltage is increased to $V_{RS} \sim 45 \mu\text{V}$. The flux coupled to the SQUID from the input coil induces the $1/f$ noise. The $1/f$ voltage noise obtained is larger than previously reported data [4] because a metal film with $R_o = 10 \Omega$ was used in the SQUID voltage input coil while the authors [4] utilized a superconducting loop. More work is being undertaken using a high- T_c superconducting loop in the input coil instead.

IV. CONCLUSION

We have characterized the voltage noise of high- T_c bicrystal SQUIDs and integrated the SQUID to form integrated SQUID voltmeters. The SQUIDs show the low frequency $1/f$ voltage noise in standard dc bias and the noise is reduced by the bias reversing technique. These data suggest that the critical fluctuation dominate the noise behavior in the junctions. Using the ac bias reversing technique in the flux-locked scheme, we further demonstrated that the flux motion also induces the $1/f$ noise. The voltage noise $S_v^{1/2}$ of voltmeters under the flux nulling condition was $0.1 \mu\text{V}/\text{Hz}^{1/2}$ at 3 Hz when a metal film with $R_o = 10 \Omega$ was used. We propose that one can reduce the voltage noise if a superconducting loop is used instead in the voltage-input loop.

REFERENCES

- [1] A. Davidson, R.S. Newbower, and M.R. Beasley, *Rev. Sci. Instrum.*, vol. 43, pp. 1626, 1972.
- [2] V. Polushkin, D. Drung, and H. Koch, "A broadband picovoltmeter based on the direct current superconducting quantum interference device with additional positive feedback," *Rev. Sci. Instrum.*, vol. 65, pp. 3005-3011, September 1994.
- [3] See, for example, Roger H. Koch, John Clarke, W.M. Goubau, J.M. Martinis, C.M. Pegrum, and D.J. Van Harlingen, "Flicker ($1/f$) noise in tunnel junction DC SQUIDs," *J. Low Temp. Phys.*, vol. 51, pp. 207-224, 1983.
- [4] A.H. Miklich, D. Koelle, F. Ludwig, D.T. Nemeth, E. Dantsker, and John Clarke, "Picovoltmeter based on a high transition temperature SQUID," *Appl. Phys. Lett.*, vol. 66, pp. 230-232, January 1995.
- [5] V. Foglietti, W.J. Gallagher, M.B. Ketchen, A.W. Kleinsasser, R.H. Koch, S.I. Raider, and R.L. Sandstrom, "Low-frequency noise in low $1/f$ noise dc SQUID's," *Appl. Phys. Lett.*, vol. 49, pp. 1393-1395, November 1986.
- [6] C.D. Tesche, "Parameter fluctuations and low frequency noise in Josephson junction devices," *Appl. Phys. Lett.*, vol. 41, pp. 99-101, July 1982.