Low Excess Flux Noise in $YBa_2Cu_3O_{7-x}$ dc SQUIDs Cooled in Static Magnetic Fields

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***Abstract* -- We have investigated the effect of device geometry on the excess low frequency 1/f noise of thin-film YBCO dc SQUIDs cooled in static magnetic fields. The key factor in eliminating this noise is the reduction of the linewidth of the SQUID loop to a value below the average separation of the flux vortices. The spectral density of the flux noise in these devices was independent of cooling field up to 33 μT in the best case. Estimates indicate that incorporating this device into a directly-coupled magnetometer would not increase the noise further.**

I. INTRODUCTION

The magnetic field sensitivity of dc SQUID magnetometers fabricated from thin films of the high-T_c superconductor $YBa_2Cu_3O_{7-x}$ (YBCO) is often limited at low frequencies by the intrinsic flux noise of the device, which has a spectral density $S_\Phi(f)$ that scales as 1/f (f is the frequency.) This is especially true when the SQUID is cooled in an ambient magnetic field B_0 such as that of the earth, approximately 50 μT. The excess noise is generated by the random hopping of flux vortices that penetrate and are trapped in the YBCO film as it is cooled through T_c. For uncorrelated vortex motion $S_\Phi(f)$ is proportional to the number of vortices which is in turn proportional to B_0. Thus one expects $S_\Phi(f)$ to scale linearly with B_0 as was demonstrated by Miklich *et al.* [1] for a YBCO SQUID cooled in static magnetic fields. For some applications, notably geophysics, it is essential to be able to cool and operate a SQUID magnetometer in the ambient field without an increase in the flux noise. In this paper we describe an investigation of the effects of SQUID geometry on the low frequency noise increase when the device is cooled in static magnetic fields. After a brief description of our fabrication and measurement techniques we discuss the results of the low-frequency flux noise measured in several field-cooled SQUIDs with two different geometries - a square washer and a narrow rectangular annulus. We demonstrate a significant reduction in the noise for the latter design. We conclude by discussing the incorporation of this type of SQUID into a directly-coupled magnetometer.

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II. FABRICATION AND MEASUREMENT

We use a pulsed KrF excimer laser to deposit a 150 nm-thick $YBa_2Cu_3O_{7-x}$ film on a $SrTiO_3$ bicrystal substrate with a 24° angle of in-plane misorientation. We then immediately evaporate a 50 nm-thick Ag film through a shadow mask for electrical contacts. We pattern the film using conventional photolithography and Ar ion milling at normal incidence with a liquid nitrogen cooled stage. Typically we make 10-15 SQUIDs with 1-2 μm wide junctions on a single 10 x 10 mm^2 chip.

We cool the SQUID in a perpendicular static magnetic field supplied by a copper-wire solenoid powered by an acid battery. Both the SQUID and solenoid are immersed in liquid nitrogen. A cold cryoperm shield encloses the SQUID and solenoid. To provide additional shielding the dewar is surrounded by three mu-metal shields. The SQUIDs are operated in a flux-locked loop with a 100kHz flux modulation and with current bias reversal at 2 kHz to eliminate 1/f noise due to critical current fluctuations.

III. RESULTS

A. Square-Washer SQUIDs

A magnetometer consisting of a square washer SQUID inductively coupled to the multiturn input coil of a flux transformer in either a flip-chip [2] or integrated [3] design combines high magnetic field sensitivity with small sensor size presenting an attractive approach for many applications. The SQUID washer is made large, say 500 x 500 μm^2, to facilitate efficient coupling [4]. Consequently we first re-examined the dependence of the flux noise on the ambient field for these large-area SQUIDs. The geometry is shown inset in Fig. 1 and the results are summarized in Table I. The SQUID washer has an outer dimension D=500 μm and an inner slit of length ℓ and width 4 μm. Devices 1-3 have a longer slit and a correspondingly higher inductance L than devices 4 and 5. As shown in Table I $S_\Phi^{1/2}(1Hz)$ increases significantly as these SQUIDs are cooled in increasing ambient fields B_0. The spectral density $S_\Phi(1Hz)$ in all cases scaled linearly with B_0. Fig. 1 shows that $S_\Phi^{1/2}(f)$ for device 5 measured at 24 μT scales as $1/f^{1/2}$ below about 300 Hz. These results suggest that the excess noise arises from the uncorrelated motion of flux vortices, the number of which scales with B_0.

TABLE I

FLUX NOISE AT 1 HZ FOR FIVE WASHER SQUIDS COOLED IN THREE VALUES OF MAGNETIC FIELD

device	D (μm)	ℓ (μm)	L (pH)	$S_\Phi^{1/2}$(1Hz) ($\mu\Phi_0$ Hz$^{-1/2}$) 0μT	24μT	61μT
1	500	250	80	31	220	330
2	500	250	80	24	240	380
3	500	250	80	16	250	400
4	500	100	40	33	120	---
5	500	100	40	5	130	180

If one were to couple a typical multilayer flux transformer with a 10 mm pickup loop and a 16-turn input coil to any of the devices 1-5 [2] to form a magnetometer, the flux noise in the SQUIDs at 24 μT would limit the magnetic field sensitivity at 1 Hz to about 400 fTHz$^{-1/2}$, an order of magnitude greater than usually obtained for the best of these sensors in zero-field [2], [3].

B. Narrow-linewidth SQUIDs and magnetometers

In an attempt to reduce the low frequency noise in an ambient magnetic field, we fabricated SQUIDs with loops in which the linewidth w is reduced to dimensions much smaller than that of the washer devices described above. If w is reduced to below $(\pi\Phi_0/4B_0)^{1/2}$, approximately the average vortex-vortex separation, it becomes energetically unfavorable for vortices to enter the film [5]. For a fixed value of w, vortices are expected to enter the superconducting film when it is cooled in fields above $\pi\Phi_0/4w^2$. To test this hypothesis we repatterned device 5 (inset Fig. 1), reducing the outer dimension D from 500 to 30 μm and thereby reducing the linewidth w to 13 μm. The flux noise measured at 24 μT (Fig. 1) is dramatically reduced, by more than two orders of magnitude in power at 1 Hz. The spectrum of the repatterned device is white down to 10 Hz and increases slightly at lower frequencies.

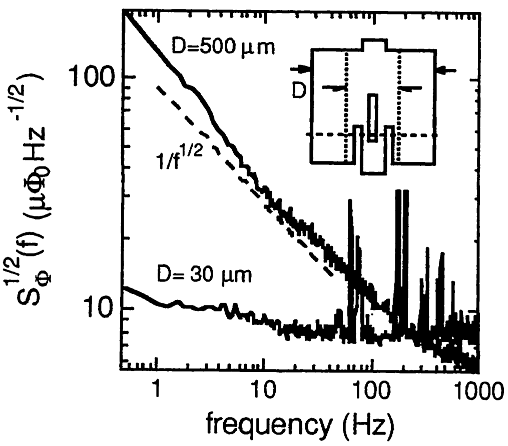

Fig 1. $S_\Phi^{1/2}$(1Hz) for device 5 shown in the inset (not to scale). The upper trace is for D=500 μm , lower trace measured after the washer has been reduced to width D=30 μm indicated by the dotted lines. Dashed line indicates grain boundary. Spikes on traces are due to 60 Hz and its harmonics and to microphonic noise.

TABLE II

COMPARISON OF PARAMETERS FOR SEVEN NARROW-LINEWIDTH SQUIDS

device	D (μm)	w (μm)	ℓ (μm)	L (μm)	B_T (μT)
6	20	8	48	40	26
7	30	13	55	40	20
8	30	13	55	40	19
9	20	8	24	20	N/A
10	30	13	55	40	20
11	12	4	40	40	33
12	12	4	40	40	33

To investigate further the effect of the SQUID configuration on the flux noise we fabricated a series of SQUIDs (inset Fig. 2) with D ranging from 12 to 30 μm and w correspondingly ranging from 4 to 12 μm. The length ℓ of the 4 μm-wide slit was adjusted to yield an inductance L of either 20 or 40 pH. Fig. 2 displays the behavior of three of these devices, fabricated in the same film. Additional parameters are summarized in Table II. For devices 7 and 8 (D=30 μm, w=13 μm), $S_\Phi^{1/2}$(1Hz) is approximately constant for B_0 up to about 20 μT. Above this threshold ambient field (B_T), $S_\Phi^{1/2}$(1Hz) increases rapidly, indicating that the flux vortices penetrate the film. For device 6 (D=20 μm, w=8 μm) the threshold field is somewhat higher, about 26 μT, as one might expect for the smaller linewidth SQUID. The threshold value of B_0 calculated from $\pi\Phi_0/4w^2$ for w=13 μm is 10 μT rather lower than the measured value, whereas for w=8 μm it is 25 μT, in good agreement with the measured B_T.

In Fig. 3 we show the frequency-dependent noise spectra for device 8 cooled in three static magnetic fields. At B_0=19.5 μT the noise below about 5 Hz has increased

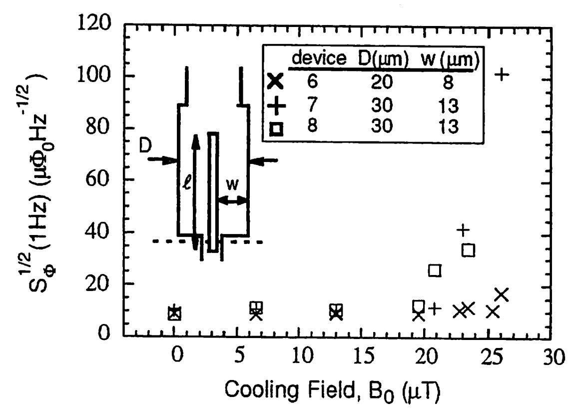

Fig 2. $S_\Phi^{1/2}$(1Hz) as function of the ambient cooling field, B_0 for three narrow-linewidth SQUIDs. Geometry is shown in the inset. Dashed line indicates grain boundary.

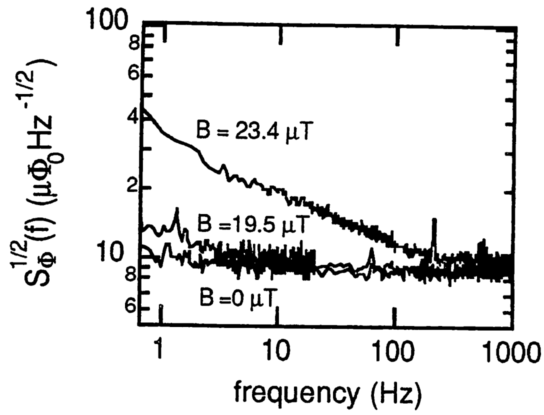

Fig 3. $S_\Phi^{1/2}(f)$ vs. frequency for device 8 cooled in three magnetic fields.

slightly above the zero-field value. Thus the onset of vortex entry occurs at a field just below this value. At B_0=23.4 μT, $S_\Phi^{1/2}$(1Hz) has increased by about a factor of 3 over the zero-field value. The power spectrum below about 200 Hz scales approximately as $1/f^{0.4}$; this slope is more shallow than what we typically observe in large-area SQUIDs (see for example Fig. 1).

Fig. 4 shows a rather different behavior for device 9 (D=20 μm, w=8 μm), in which $S_\Phi(f)$ increases linearly with B_0. This device was fabricated in the same film as devices 6-8 and suggests a variation in film quality, very likely at the edges. We note that Sun *et al.* [6] in their experiments on magnetic hysteresis found that the field at which vortices entered the film depended critically on the quality of the edges. Out of nine narrow-linewidth SQUIDs that we examined two exhibited the behavior shown in Fig. 4. Nonetheless, for a given cooling field, the noise in device 9 is an order of magnitude smaller than in the large-washer SQUIDs.

On a separate bicrystal we fabricated 10 small directly coupled magnetometers consisting of a SQUID whose outer dimension D ranged from 12 to 30 μm coupled to a pickup

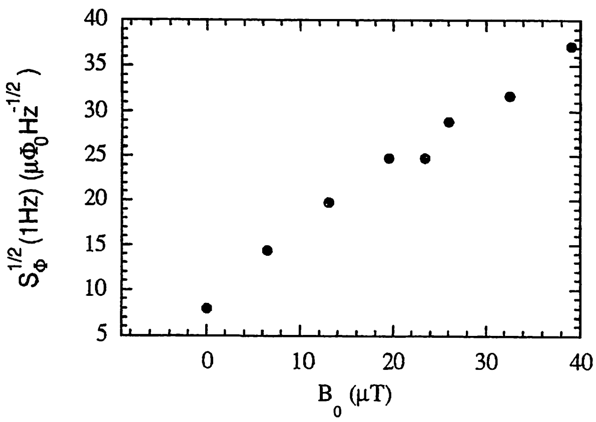

Fig 4. $S_\Phi^{1/2}$(1Hz) as a function of the.cooling field for device 9 with geometry shown inset in Fig. 2. One other device showd similar behavior.

loop 1.8 mm by 3.8 mm. Table II summarizes the parameters and measured threshold fields B_T for vortex penetration for three representative magnetometers, devices 10-12. For device 10 (D=30 μm, w=13 μm) B_T is about 20 μT, as for devices 7 and 8 which have the same linewidth. For devices 11 and 12 (D=12 μm, w=4 μm) the noise increases at B_T = 33 μT, a factor of about 3 below the predicted value of 102 μT.

IV. Discussion

It is clear that the narrow-linewidth SQUIDs generate considerably less flux noise than the large-washer devices when cooled in comparable ambient fields. It is impractical, however, to inductively couple such a small SQUID to a multiturn flux transformer to produce a sensitive magnetometer. However, one could still use such SQUIDs in a directly-coupled magnetometer [7] and we briefly discuss the influence of the 1/f noise generated by the pickup loop. We consider a magnetometer with a square pickup loop of outer and inner dimension d_1 and d_2. The linewidth of the pickup loop $w_p = (d_1 - d_2)/2$ is typically 1 mm or more to maintain a low inductance L_p. Therefore vortices are expected to penetrate the film even in low cooling magnetic fields.. Vortex motion in the pickup loop generates screening currents which, in turn, couple flux noise into a fraction α_d of the SQUID inductance L. We can estimate the magnitude of this "indirect" flux noise following the model of Ferrari *et al.* [8]. For $\mathcal{N}$ uncorrelated vortices per unit area with a radial motion spectral density $S_r(f)$ in the film of the pickup loop, the spectral density of this flux noise is

$$S_\Phi^{in}(f) \approx \mathcal{N} S_r(f)\Phi_0^2\,\alpha_d^2 L^2\,(\ell_p/w_p)/L_p^2 \ , \qquad (1)$$

where $\ell_p = 2(d_1 + d_2)$ is the average perimeter of the pickup loop. It was shown [8] that $4\mathcal{N} S_r(f)\,\Phi_0^2 \approx S_\Phi^U(f)$, the noise of an unpatterned YBCO film measured by a low-T_c SQUID placed directly over it. For representative values $d_1 \approx 10$ mm, $d_2 \approx 2$ mm, $L_p \approx 5$nH, $L \approx 40$pH, and $\alpha_d \approx 1$ we find $S_\Phi^{in}(f) \approx 10^{-5}\, S_\Phi^U(f)$. Furthermore, for laser-deposited YBCO films cooled in $B_0 = 50$ μT we have measured [1] $S_\Phi^U(1Hz) \approx 10^{-9}\,\Phi_0^2 Hz^{-1}$, so that $S_\Phi^{in}(1Hz) \approx 10^{-14}\,\Phi_0^2 Hz^{-1}$. This value is several orders of magnitude less than the noise measured in devices 6-12 (Table II) in fields below the threshold for flux entry. Thus the indirect noise generated by vortices in the pickup loop is negligible compared with the intrinsic noise of the SQUID.

In summary, we have shown that the geometry of a YBCO SQUID significantly affects the flux noise measured in an ambient magnetic field. In the best case, reducing the linewidth of the SQUID loop below the average vortex-vortex spacing eliminated the excess 1/f noise in fields up to 33 μT. It remains highly desirable to increase this threshold field above 50 μT. Further reduction in the linewidth together with improvements in the processing technology, especially with regard to the quality of the edges, may facilitate the desired enhancement. Finally, incorporating a narrow-linewidth SQUID into a directly-coupled magnetometer presents a viable sensor for field-cooled operation since vortex motion in the pickup loop is expected to couple a negligible amount of noise into the SQUID.

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