Low-frequency noise and linearity of $YBa_2Cu_3O_7$ dc SQUID magnetometers in static magnetic fields

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***Abstract*—We have investigated the low-frequency noise of a field-cooled dc SQUID magnetometer from $YBa_2Cu_3O_7$ in magnetic fields up to 200 μT, both before and after it was patterned with holes to reduce the maximum structural width of the pickup-loop. We find, that even in low fields the noise of the unpatterned magnetometer steadily increases with the applied field. However, after the patterning for the holes, the noise remains at the zero field level up to a threshold field of 35 μT and is always less than in the unpatterned case. This threshold field is also found in field dependent measurements of the total harmonic distortion. Moreover, the influence of the patterning on the effective area of the magnetometer is discussed.**

I. Introduction

A severe obstacle for many practical applications of SQUID magnetometers from high temperature superconductors (HTS) has long been the increase of low-frequency noise when the magnetometer is operated in an ambient magnetic field like the earth's field of about 50 μT. This excess noise is caused by the thermally activated random hopping of magnetic flux vortices between their pinning sites [1]. The vortices are either created when the magnetometer is cooled below its critical temperature T_c in an ambient field, or they are introduced into the film by the Lorentz force from shielding currents [2]. The spectral density S_Φ of the flux noise typically scales with $1/f$ as a function of the frequency f and therefore adversely affects low-frequency applications like biomagnetism or geophysical measurements. Since the number of vortices is proportional to the applied field B_0, S_Φ is expected to scale linearly with B_0. Moreover, the amount of noise is strongly dependent on the epitaxial quality of the involved superconducting thin-films [3], [4]. Noise measurements in dependence on the applied field have been reported for bare dc SQUIDs [5], [6], directly-coupled magnetometers [5], [7]–[9], rf SQUIDs [10], [11] and magnetometers from HTS multilayers [12].

Recently, Dantsker *et al.* made several suggestions for the design of HTS SQUID devices in order to reduce the amount of trapped flux. They are based on the reduction of the linewidth of the SQUID body, so that it becomes energetically unfavourable for flux to enter the film. An estimation for the threshold field of flux entry is given by

$$B_T = \frac{\pi \Phi_0}{4w^2}, \tag{1}$$

where w is the linewidth of the film [13], [14]. Most groups have favoured the slotted design, where the SQUID is provided with many parallel slots which divide the SQUID body in narrow filaments to increase B_T. Here, we present measurements on a directly-coupled magnetometer, both before and after it was patterned with holes to reduce the maximum structural width of the pickup-loop. To our knowledge, these are the first measurements, which directly compare the effects of this kind of patterning for the same device. The comparison of different devices may be misleading, because of a variable microstructural or epitaxial quality of the involved superconducting thin-films. Additional measurements of the total harmonic distortion (THD) characterize the linearity of the magnetometer with holes in dependence on the applied field.

II. Device Preparation

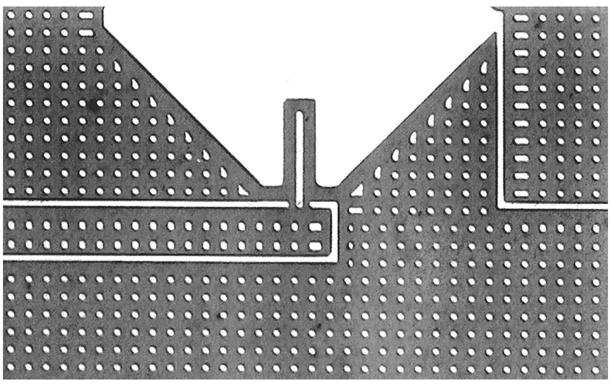

Fig. 1. Micrograph of the magnetometer part around the SQUID-loop after it was patterned with holes. The holes have a diameter of about 4 μm and the linewidth between them is about 5.2 μm.

Our directly-coupled dc SQUID magnetometers are prepared from a single epitaxial $YBa_2Cu_3O_7$ thin-film on a symmetrical (100) $SrTiO_3$ bicrystal with 24° misorientation angle. We typically use films of 120 nm thickness, which are deposited by KrF excimer laser deposition.

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TABLE I
TRANSPORT PROPERTIES OF THE INVESTIGATED MAGNETOMETER AT $T = 77$ K, BEFORE AND AFTER THE PATTERNING OF THE HOLES.

		before	after	
Voltage swing	ΔV	26	27	μV
Critical current[a]	I_0	107	76.5	μA
Normal resistance[a]	R_n	2.1	2.8	Ω
Sensitivity	B/Φ	9.203	8.980	nT/Φ_0
Effective area	$A_{\text{eff}} = \Phi/B$	0.225	0.230	mm^2

[a]Values given per junction.

After the patterning with conventional photolithography and argon plasma etching, the magnetometers are treated in an oxygen plasma. Finally, the contact pads are covered with silver to reduce the contact resistance. The magnetometer layout is similar to the one introduced by Lee *et al.* [15] with a washer-type pickup-loop of an outer dimension of 8.3 mm and an inner hole size of $3 \times 3\,\text{mm}^2$. The SQUID-loop has an outer area of $16 \times 56\,\mu\text{m}^2$ and an inner hole of $4 \times 50\,\mu\text{m}^2$, from which we calculate an inductance of 60 pH, including the kinetic contribution. The bicrystal junctions are nominally $3\,\mu$m wide. After the first characterization of the magnetometer with solid pickup-loop, it was patterned a second time using a net-like photomask. We obtained a linewidth of about $5.2\,\mu$m and circular holes with a diameter of about $4\,\mu$m across the whole pickup-loop. Fig.1 depicts a micrograph of the region around the SQUID-loop.

III. MEASUREMENTS

All measurements were performed in liquid nitrogen inside of a triple mumetal shield. The magnetic field B_0 was applied with a Helmholtz coil, that was supplied by a large capacity lead-acid battery and an appropriate resistor. The flux density noise resulting from the current noise in the coil is less than $85\,\text{fT}/\sqrt{\text{Hz}}$ at 3 Hz and $B_0 = 100\,\mu$T and does not significantly contribute to the measured noise values. The noise measurements were made in fluxed-locked-loop (FLL) mode with bias current reversal to reject the low-frequency noise from critical current fluctuations in the junctions. In all field dependent measurements the magnetic field was applied while the magnetometer was heated above T_c, and it remained on during the cooling and the measurements. Hence, no shielding currents were generated as in a switching process. The magnetometer properties before and after the second patterning step for the holes are listed in Table I. After the treatment, I_0 and R_n were somewhat changed, presumably due to a slight oxygen loss in the junctions, since no second plasma oxidation was carried out. Surprisingly, the patterning had only a minor effect on the sensitivity of the device. The effective area increased by about 2%, although the character of input coupling completely changed. With the solid pickup-loop, flux is focused to some extent into the loop by the Meissner effect. In the patterned device, however, this effect is substituted by the flux quantization, which keeps the flux in the holes constant at integer flux quanta. Thus, flux changes must be partly focused into the pickup-loop again. Obviously, there is no significant quantitative difference between both effects. However, a difference is found in field dependent measurements. For the solid device, we find a slight increase of the effective area with a variation of about $\partial A_{\text{eff}}/\partial B \simeq 1.6 \times 10^{-4}\,\text{mm}^2/\mu\text{T}$, whereas it is a decrease by nearly the same value $-1.5 \times 10^{-4}\,\text{mm}^2/\mu\text{T}$ for the patterned device. The reason for this behaviour is not yet clear. This effect leads to a nonlinear response of the magnetometer and therefore contributes to its THD. However, a calculation for $B_0 = 100\,\mu$T and a signal amplitude of 10 nT yields THD ≈ -110 dB, which is much less than the measured values discussed below.

A. Low-frequency noise in static magnetic fields

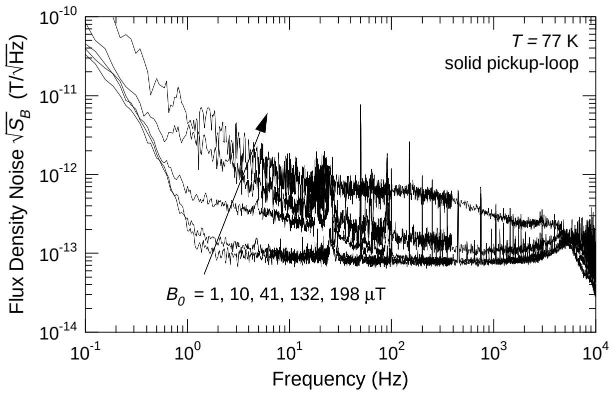

Fig. 2. Flux density noise spectra of the unpatterned magnetometer for different cooling fields B_0.

Fig. 2 depicts several flux density noise spectra for the unpatterned magnetometer in different cooling fields B_0. We find an increasing low-frequency noise with B_0 from the growing number of trapped vortices in the film. The spectra for $B_0 = 41\,\mu$T and $198\,\mu$T include a Lorentzian contribution, caused by the random telegraph signal (RTS) from a predominant two-level fluctuator. Fig. 3 shows the noise values at the frequency 3 Hz in dependence on B_0, before and after the holes were patterned into the pickup-loop. In the unpatterned case, the low-frequency noise increases with B_0 even for the lowest cooling fields, whereas it remains approximately constant below a threshold field $B_T \simeq 35\,\mu$T in the patterned case. Moreover, we find, that for all values of B_0, the magnetometer with holes remains markedly less noisy than without the holes. In the unpatterned case, the noise below B_T presumably results from the motion of vortices near the SQUID-loop, which is directly coupled into the SQUID, since the indirect component from noise currents in the pickup-loop is strongly suppressed by the poor coupling between the inductances of the pickup-loop and the SQUID [13]. In both cases, we observed a significant increase of noise above B_T. We attribute this to flux entry into the SQUID-loop, although a somewhat larger thresh-

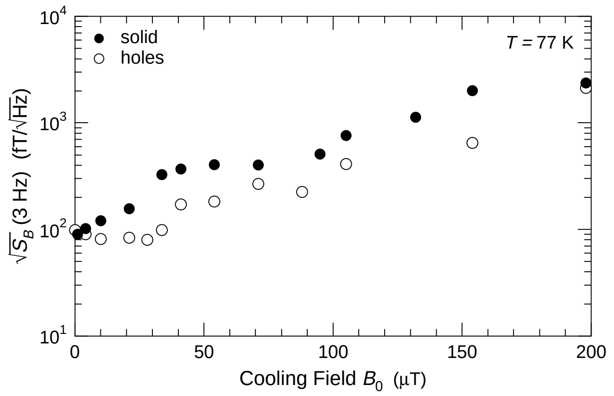

Fig. 3. Flux density noise at 3 Hz vs cooling field B_0 for the directly coupled magnetometer, before (•) and after it was completely patterned with holes (∘).

old field of $42\,\mu$T for the measured width $w = 6.2\,\mu$m is expected from (1). In particular in the unpatterned case, the noise values above the threshold field remain on a nearly constant level up to $B_0 \simeq 80\,\mu$T. This noise was caused by the dominating RTS from a single fluctuator and therefore does not scale with B_0. For higher values of B_0, it is covered by the noise of the remaining vortices.

B. Linearity

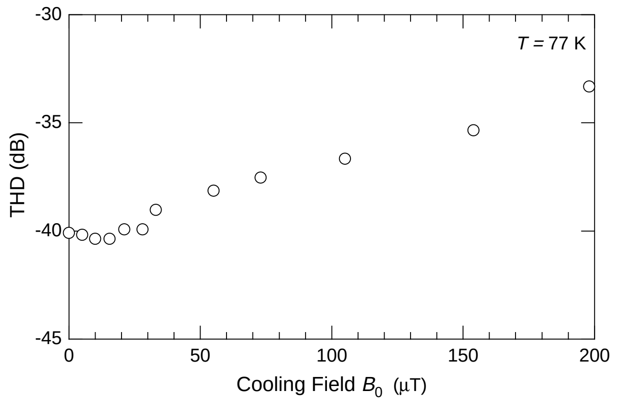

Fig. 4. Measured total harmonic distortion (THD) of the patterned magnetometer in dependence on the cooling field B_0 for a sinusoidal magnetic signal with the peak-to-peak amplitude $\Delta B = 20\,$nT and the frequency $f = 518\,$Hz.

Nonlinear behaviour of a SQUID magnetometer can result from the inelastic motion of vortices in the magnetometer body [16]. Thus, the degree of nonlinearity is expected to depend on the number of vortices and therewith on the cooling field. To measure the magnetometer linearity, we applied a sinusoidal magnetic signal with a peak-to-peak amplitude of 20 nT and the frequency $f = 518\,$Hz. The output voltages from the signal source and the FLL electronics were electronically subtracted, to obtain a maximum suppression of the harmonics of the test signal. The residual signal was measured with a spectrum analyzer. Fig. 4 shows the amount of THD of the patterned magnetometer in dependence on the cooling field. The THD values show a very similar dependence on B_0 as is found in the noise measurements. The THD remain nearly constant for fields below a threshold and increased for cooling fields beyond this value, whereby the threshold field agrees well with the value found in the noise measurements. We therefore conclude, that the nonlinearity of the field-cooled magnetometer is caused by the motion of the vortices.

IV. Conclusions

In conclusion, we have shown, that the noise of a SQUID magnetometer cooled in a magnetic field can be significantly lowered by reducing its linewidth through holes in the pickup-loop. The observed threshold field is attributed to flux entry into the SQUID-loop, which should be made narrower in future layouts. The patterning does not significantly affect the effective area of the device. The magnetometer THD is dependent on the cooling field.

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