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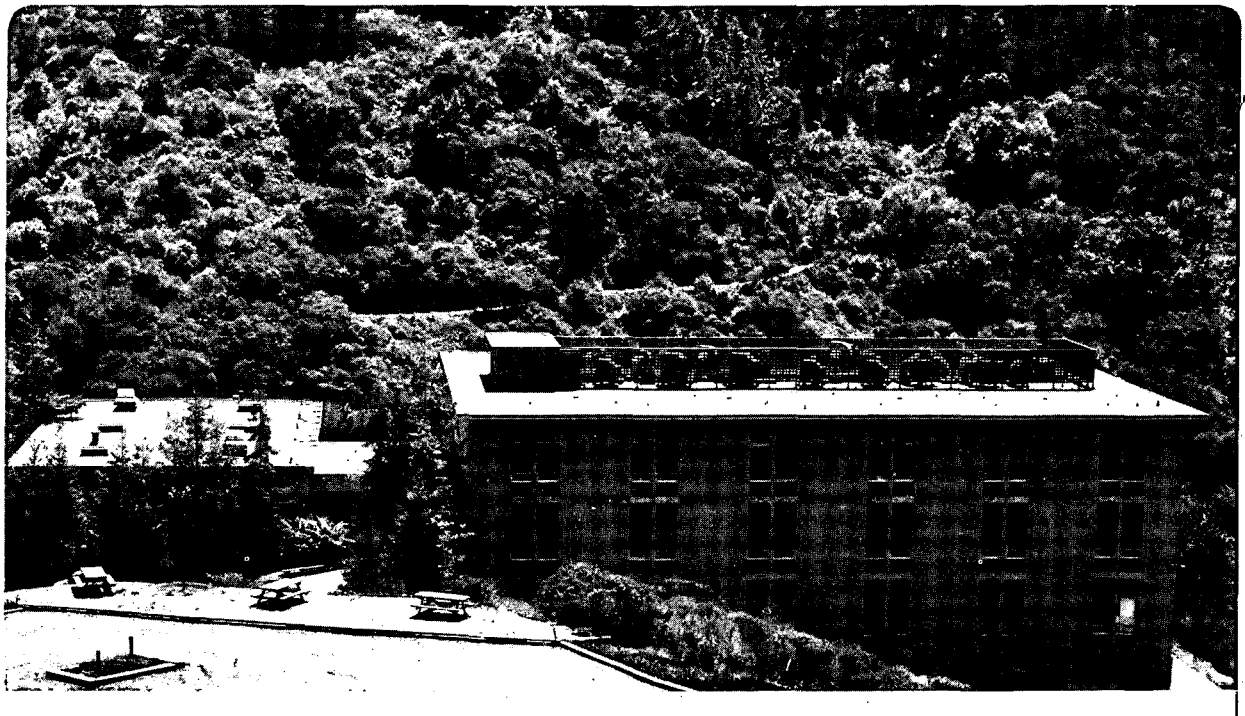

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THIN-FILM FLUX TRANSFORMERS OF $YBa_2Cu_3O_{7-x}$

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Abstract

Using a three-layer *in situ* laser deposition process, we have constructed superconducting thin-film flux transformers of $YBa_2Cu_3O_{7-x}$ (YBCO). The transformers are designed for efficient coupling to a planar thin-film dc SQUID, have 0.7cm^2 magnetic field pickup areas, and 10-turn input coils. When coupled to a low transition temperature (T_c) SQUID, the resulting hybrid magnetometer exhibits excess low frequency flux noise which arises in the transformer. This noise depends on the geometry of the flux transformer, and the observed behavior agrees with model calculations of the expected contribution from flux motion in the YBCO. The hybrid magnetometer attains a magnetic field sensitivity of about 0.9pTHz$^{-1/2}$ at 1Hz with the transformer at 60K; the rms noise decreases as $1/f^{1/2}$ up to a frequency f=1kHz. We believe that the sensitivity is high enough for use, for example, in magnetocardiography.

Introduction

The heart and brain produce weak magnetic fields which can be detected with sensitive magnetometers.[1] The magnetic fields are intrinsically very weak and the sources are of limited spatial extent. As a result, the magnetic fields are significant only over limited areas close to the source. At present, only magnetometers based on the dc Superconducting QUantum Interference Device (SQUID)[2] are sensitive enough to measure, say, the magnetic fields from the visually evoked response from the human brain (maximum signal strength of about 100fT).[1] Such magnetometers have two superconducting components, the SQUID itself and a flux transformer.[1-3] A flux transformer is a closed superconducting circuit consisting of a pickup loop which senses the applied field and a smaller area multiturn coil which couples flux into the SQUID.

The purpose of the flux transformer is to increase the magnetic field sensitivity of the SQUID. However, for sources of limited spatial extent, increasing the pickup area of a sensor may not lead to an increased sensitivity. Suppose that the field is constant over a region with side length 2b and area $A_{max}=4b^2$. In principle one can use either a bare SQUID of area A_{max} or a smaller SQUID with a flux transformer of area A_{max}. Which arrangement is more sensitive?

Consider an annular shaped SQUID with inner hole diameter 2a and outer diameter 2c. For c>>a, the SQUID will have an inductance $L=2.5\mu_0 a$ and an effective magnetic field pickup area $A_{eff}=4ac$.[4] Because of thermal noise effects, it is not possible to make L arbitrarily large, and we can thus consider 2a as a fixed parameter. The sensitivity of a bare SQUID to magnetic fields is just $S_B=S_\Phi/(16a^2c^2)$, where S_Φ is the flux noise in the SQUID. The maximum sensitivity, which will occur for c as large as possible, i.e. c=b, is $S_B=S_\Phi/(16a^2b^2)$. The field sensitivity of a SQUID and flux transformer is $S_B=S_\Phi (L_i+L_p)^2/(\alpha^2 L L_i A_p^2)$ where L_i is the input coil inductance, L_p is the pickup coil inductance, α is the coupling coefficient, and A_p is the area of the pickup coil. The maximum sensitivity will occur when the input coil and pickup coil are of approximately equal inductance, $\alpha\approx1$, and $A_p=A_{max}$; in this case $L_p\approx2.5\mu_0 b=(b/a)L$ and $S_B=S_\Phi/(4ab^3)$.[4] Thus, the transformer and SQUID will be more sensitive than a bare SQUID provided that b>4a. For typical low T_c (a=100μm) or high T_c (a=20μm) SQUIDs this condition is satisfied for b as small as 0.5mm.

Obviously, biomagnetic sources function at room temperature whereas the superconducting sensors must operate in a cryogenic environment. The discovery of high transition temperature (T_c) superconductors has enabled the development of SQUIDs[5] and flux transformers[6-7] which operate at 77K. This temperature is high enough that superconducting devices need not be shielded from room temperature thermal radiation in order to operate (of course it is necessary to prevent solid thermal contact). The development of sensitive high T_c magnetometers may thus enable the pickup loop to be brought closer to the source, allowing increased spatial or field resolution.

In this paper, we first discuss the expected noise from a thin-film planar flux transformer and then describe the construction and behavior of a hybrid dc SQUID magnetometer formed by coupling a low T_c Nb-PbIn SQUID to a $YBa_2Cu_3O_{7-x}$ (YBCO) flux transformer.

Expected Flux Noise from the Transformer Components

In an ideal magnetometer, the sensitivity to magnetic fields will be limited only by thermally generated noise in the SQUID.[8] In this case, when the SQUID is coupled to a matched flux transformer, it can be shown that the magnetic field sensitivity will be $S_B=8k_BTLL_i/(R\alpha^2A_p^2)$. For typical parameters $A_p=1cm^2$, $\alpha^2=0.5$, $L_i=20nH$, L=40pH, SQUID shunt resistance R=1Ω, and temperature T=77K one finds $S_B=(1.2fT)^2Hz^{-1}$. This sensitivity is remarkably high and demonstrates that, at least in principle, a 77K SQUID magnetometer can be sensitive enough to measure most biomagnetic sources of interest.

Unfortunately, existing high-T_c SQUIDs typically display excess low frequency noise which is considerably larger than the white thermal noise.[5] We have also found that the motion of magnetic vortices in the high-T_c flux transformers can be a source of noise, and that this motion limits the sensitivity of our hybrid magnetometer.[9] Moving vortices will couple noise into the SQUID by two distinct mechanisms. In the first, which we call "direct noise," the SQUID senses directly the magnetic field produced by the vortex. In the second, which we call "indirect noise," the SQUID senses the screening current in the flux transformer induced by the motion of vortices.

The magnitudes of the direct and indirect noise from the transformer will depend on a number of parameters, which we can divide roughly into materials-related factors (film composition, microstructure, or temperature) and geometrical factors (number of vortices in the film, shape and size of transformer and SQUID, SQUID-transformer coupling). The materials factors can be thought

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of as producing vortex motion in the film, while the geometrical factors are essentially transfer functions giving the flux change produced in the SQUID by the motion.

At present, it is not possible to give useful theoretical predictions for the magnitude of the materials factors. However, given the noise in an unpatterned film, the geometrical factors can be used to predict the noise which would be seen if the film were patterned into a transformer. Accordingly, we will now consider the geometrical factors for three cases of interest: (1) the direct noise from a thin-film sample which is small compared to the SQUID, (2) the indirect noise from a closed loop which couples flux into the SQUID, and, for comparison, (3) the direct noise from a large thin film placed over the SQUID. For these calculations we model the SQUID as a thin-film ring of inner hole radius a and outer radius c.

Case 1: Small Structure

The dependence of the noise on the size of a film can be understood qualitatively by considering the noise produced by a thin superconducting line of width w and length ℓ. At a distance $r \gg w$ from the line, the magnetic field produced by a vortex in the line will have a dipolar dependence, and it can be shown that the dipole moment is roughly proportional to the linewidth. Thus, the field far from the line will be $B \propto w/r^3$. The flux noise sensed by a SQUID a distance r away will then be $S_\Phi \propto (\partial B/\partial r)^2 \ell w \mathcal{N}$, where $\mathcal{N}$ is the number density of vortices in the film and ℓw is the surface area of the line. On calculating the derivative, one finds that $S_\Phi \propto \ell w^3 \mathcal{N}/r^8$. Thus the noise from objects which are far from the SQUID or have small line widths will be completely negligible.

We now consider explicitly the noise produced by the input coil's "crossunder," a small line which provides an electrical connection to the inside turn of the input coil, and which forms a relatively small structure near to the SQUID (see Fig. 1). The main difficulty is to calculate the flux Φ coupled into the SQUID by a vortex in the line. We solve the problem by considering the reciprocal problem: find the flux Φ'' that a SQUID with flux Φ' in it would apply to a vortex in the line. The mutual inductance M_v between the SQUID and a vortex in the crossunder can then be written as $M_v = L\Phi''/\Phi'$, where $L=2.5a\mu_0$ is the SQUID inductance.[4] To estimate Φ'', we model the vortex as a circular hole of radius λ (the penetration depth) at radial distance r in the crossunder, and the SQUID as a monopole source of magnetic field in the upper half-plane. With this model, $\Phi''=\Phi_0\lambda w_{cr}\, d/\pi(r^2+d^2)^{3/2}$, where w_{cr} is the crossunder linewidth. We have taken $2\lambda w_{cr}$ as an estimate of the effective sensing area of the vortex.[4] The flux Φ coupled from the vortex into the SQUID is then $M_v\Phi_0/L_v \approx \Phi_0 w_{cr} a d/\pi(r^2+d^2)^{3/2}$, where $L_v=2.5\mu_0\lambda$ is the self-inductance of a hole of radius λ. If we assume there are $\mathcal{N}$ uncorrelated vortices per unit area in the film, each with a spectral density $S_r(f)$ for radial motion at frequency f, the spectral density of the flux noise from the entire crossunder becomes

$$S_\Phi^{(cr)}(f) = \frac{\mathcal{N} w_{cr}\Phi_0^2 S_r(f)}{d^5}\left(\frac{3aw_{cr}}{\pi}\right)^2 \int_{a/d}^{c/d} \frac{z^2 dz}{(1+z^2)^5}. \quad (1)$$

As expected, the direct noise scales as the cube of the linewidth w_{cr}. We have found a similar expression for the noise due to the turns of the coil.[9]

Case 2: Closed Loop Term

The motion of a vortex along a line in the transformer produces no applied flux change in the transformer. On the other hand, motion from one side of a line to the other produces an applied flux change of Φ_0. An applied flux change $\Phi_0\delta r/w$ in the transformer due to the motion δr of a vortex in a line of width w produces a screening current $I_i=\Phi_0\delta r/[w(L_i+L_p)]$ and a flux $\delta\Phi=MI_i$ in the SQUID, where L_i and L_p are the inductances of the input coil and pickup loop, and $M=\alpha(LL_i)^{1/2}$ is the mutual inductance between the input coil and the SQUID. Thus, the spectral density of the indirect noise is $\mathcal{N}[S_r(f)/w^2]w\ell M^2/(L_i+L_p)^2$ for a distribution of vortices in a line of length ℓ, and the total indirect noise from the transformer is

$$S_\Phi^{(in)}(f) = \frac{\mathcal{N} S_r(f)\Phi_0^2 M^2}{(L_i+L_p)^2}\left(\frac{\ell_i}{w_i}+\frac{\ell_{cr}}{w_{cr}}+\frac{\ell_p}{w_p}\right), \quad (2)$$

where ℓ_i, ℓ_{cr} and ℓ_p are the lengths of the input coil, crossunder and pickup loop, respectively.

Case 3: Large Thin Film

When a vortex moves in the film a distance δr along the radial direction, the flux Φ in the SQUID changes by $\delta\Phi=(\partial\Phi/\partial r)\delta r$. Movement in the azimuthal direction produces no flux change in the SQUID. For a distribution of vortices, the spectral density of the flux noise measured by the SQUID then becomes

$$S_\Phi = 2\pi\mathcal{N} S_r(f)\int_a^c \left(\frac{\partial\Phi}{\partial r}\right)^2 r\,dr. \quad (3)$$

We now estimate $\partial\Phi/\partial r$ for a film placed a distance d from the SQUID, where $d \ll (c-a)$. We have found that this system is analogous to a two-dimensional electrostatic problem: The SQUID is equivalent to a coaxial line in which the inner solid conductor has radius a and the outer conducting tube radius c; both conductors are grounded. A vortex in the film becomes a line charge at radius r

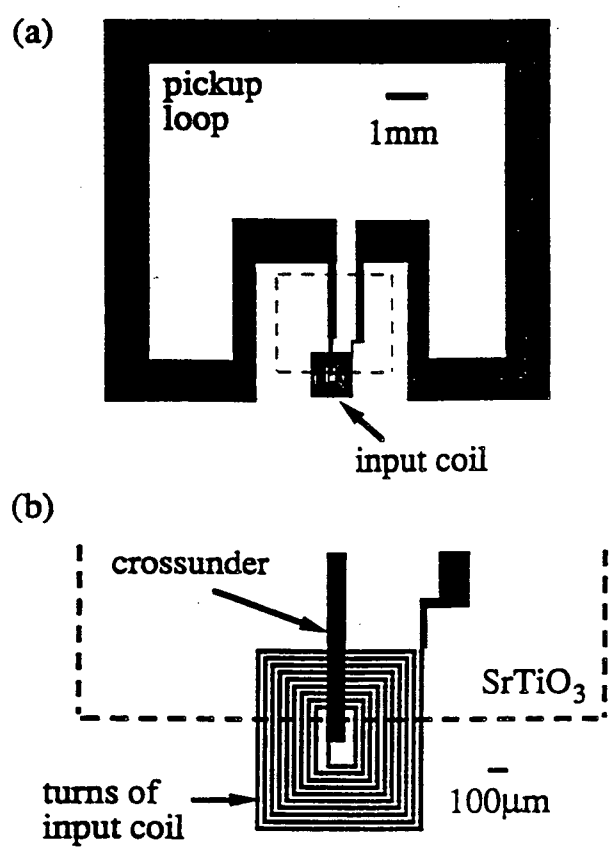

Figure 1. (a) Plan view of thin-film flux transformer, (b) detail of 10-turn input coil.

($a \le r \le c$); the charge induced on the inner conductor is equivalent to the flux coupled into the SQUID. Using the method of images,[10] we find that the flux Φ coupled into the SQUID is

$$\Phi(r) = \frac{\Phi_0}{\ln(a/c)}\left[\ln\left(\frac{r-a}{c-r}\right) + \sum_{j=1}^{\infty}(-1)^j \ln\left(\frac{a-a_j}{c-a_j}\right) + \sum_{j=1}^{\infty}(-1)^j \ln\left(\frac{c_j-a}{c_j-c}\right)\right]. \quad (4)$$

Here, $a_j = r(a/c)^j$ (j even), $(a^2/r)(a/c)^{j-1}$ (j odd) and $c_j = r(c/a)^j$ (j even), $(c^2/r)(c/a)^{j-1}$ (j odd) are the positions of the jth image charge on the inner and outer conductor, respectively. Equation (3) can now be evaluated numerically using Eq. (4) for $\Phi(r)$.

The Total Flux Noise From the Transformer

The total noise produced by the transformer will be the sum of the indirect noise and the direct noise from all of the parts of the transformer. We note that there is a partial correlation between the direct and indirect noise terms which should be found before the total noise can be computed. However, the correlation is relatively small and, as we will see below, the indirect term greatly dominates. Therefore, we can neglect this correlation for practical estimates of the noise.

Given our transformer geometry, we can now calculate the expected level of noise from the transformer. We have used the values L=0.44nH, L_i=70nH, L_p=20nH, α=0.5, a=0.1mm, c=0.5mm, d=0.1mm, w_i=20μm, ℓ_i=12mm, w_{cr}=100μm, ℓ_{cr}=0.1mm, w_p=1mm, l_p=40mm. We find that in this configuration the direct noise from the crossunder should be only about 3% of the noise from a full film. On the other hand, we find that the total noise in the transformer is dominated by the indirect term, which is about 30% of the noise from a full film. This indirect noise is dominated by the motion of vortices in the input coil because of the large ratio ℓ_i/w_i=1200 in Eq. (2). By contrast, because of their relatively narrow linewidth, the turns of the input coil produce direct noise which is only about 0.038% of the noise from a full film.

The Flux Transformers

In our transformers, the overall size of the pickup loop is limited to approximately 0.7cm2 by the size of the substrate (see Fig. 1). We choose a pickup coil linewidth of 1mm to keep the inductance small. The input coil is designed for coupling to our 1mm diameter low T_c SQUIDs and has an outer dimension of 1mm and 10 turns of 20μm linewidth.[11] The inductance of the input coil depends on how tightly it is coupled to the SQUID; it is about 70nH in the configuration used, so that the matching is not optimized for the coupling we were able to obtain. The fabrication of the transformer has been described in detail elsewhere.[11,12]

Transformer Magnetic Field Response and Noise

The transformers were tested one at a time by mounting them on a temperature-controlled stage approximately 100μm from a conventional planar thin-film Nb-PbIn dc SQUID.[13] The system is shielded from external magnetic noise and the SQUID, maintained at 4.2K, is operated in a flux-locked feedback loop. This arrangement allows us to measure the temperature dependent properties of the transformer using a low noise SQUID with well-understood behavior. Figure 2 shows the response of transformers TØ and T1 to an applied magnetic field as a function of the transformer temperature. Above the transition temperature of the transformer, the response is just that of the SQUID alone. Below the transition temperature, the response is larger and of negative sign, demonstrating that the transformer is operating. The sign difference arises from a deliberate choice of winding sense in the input coil,

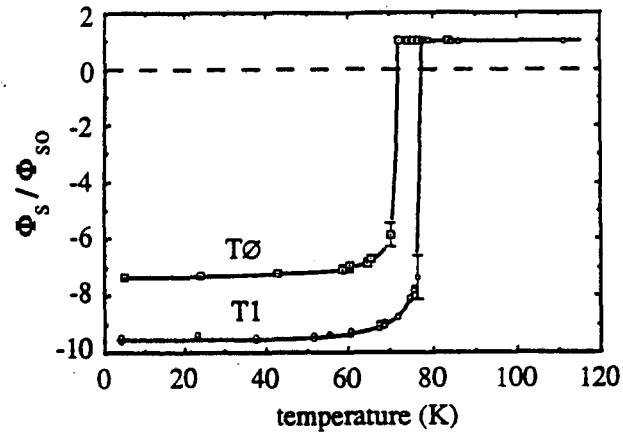

Figure 2. Response of the SQUID to an applied magnetic field vs. the flux transformer temperature for transformers TØ and T1; Φ_s is the total flux coupled into the SQUID and Φ_{so} is the flux coupled into the SQUID in the absence of the flux transformer.

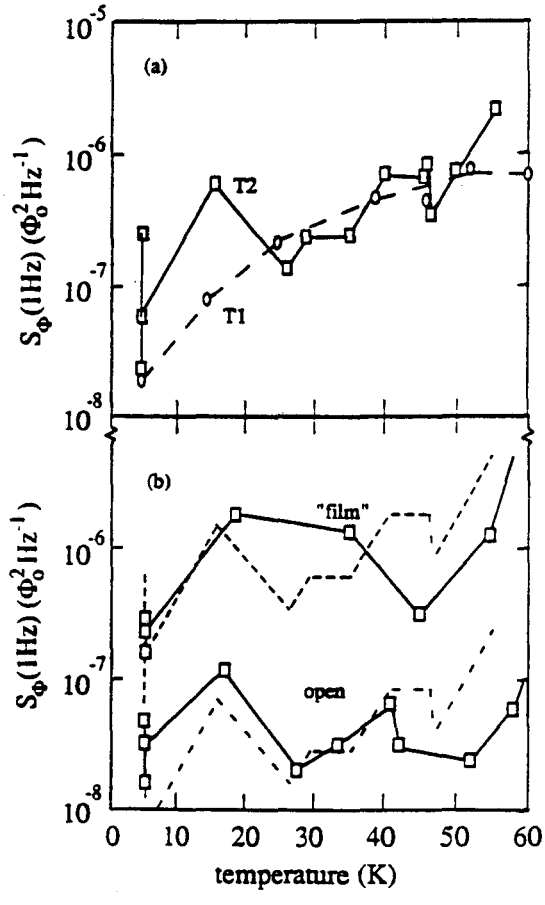

Figure 3. (a) Flux noise spectral density S_Φ measured by the SQUID at 1Hz for flux transformers T1 and T2 vs. transformer temperature; (b) dashed lines show expected noise and solid lines show measured noise for T2 with the SQUID placed over the 1mm wide strip forming part of the pickup loop (upper traces), and over the input coil when the pickup loop is opened (lower traces).

made to provide a clear signature that the transformer is working. We believe that the transition temperatures are somewhat reduced because of film degradation during the ion milling. Nevertheless, T1 operates up to 77K. From the magnitude of the responses and the inductance of the transformers, we can deduce coupling coefficients α=0.4 and 0.5 for TØ and T1 respectively. The difference in coupling is probably attributable to small differences in the separation between the SQUID and input coil.

We measured the low frequency noise in two YBCO flux transformers, T1 and T2.[13] With the SQUID carefully aligned over the input coil, the spectral densities of the noise from the two transformers were comparable, and scaled approximately as 1/f. This noise is considerably greater than that due to the SQUID alone and arises in the transformer. The temperature dependences of the magnitude of the noise in the two transformers were similar, as shown in Fig. 3(a).

After completing field response measurements on T2, we scribed open the pickup loop and remeasured the noise. This procedure required us to remove the transformer from the SQUID and subsequently remount it; we believe the separation was the same to within 20μm. The noise in the opened transformer [Fig. 3(b)] was lower by a factor of about 10. This large reduction is consistent with the noise in the closed loop being dominated by indirect noise. The observed magnitude is also consistent with that expected from the direct noise in the crossunder. Finally, we moved the 1mm strip of part of the pickup loop over the SQUID, and remeasured the noise to obtain an estimate of $S_\Phi(f)$. The linewidth of the pickup loop is large enough that the noise should be the same as the SQUID would measure from a large unpatterned film. The observed noise was roughly a factor of three higher than from the closed transformer, as expected.

The temperature dependence of the noise shown in Fig. 3 is different if the noise is measured in the open coil, the closed coil, or the film. The observed agreement in the magnitude between the model and the data is thus only rough. However, this behavior should not be too surprising because we expect that for the three cases the noise was due to the motion of vortices in three completely different regions of the transformer. Our model comparison assumed that the materials factors were the same in these three regions; this is unlikely to be precisely true because the parts were subjected to somewhat different processing.

Conclusions

From the observed level of flux noise, we find the magnetic field sensitivity of the hybrid magnetometer to be $0.9 pTHz^{-1/2}$ at 1Hz and 60K. This noise is dominated by the motion of vortices in the input coil of the transformer which couples noise into the SQUID via changes in the induced current in the transformer. With modest improvements in the flux noise from the films, the hybrid magnetometer should be sensitive enough to detect most of the signals generated by the heart. More substantial improvements are needed to detect most of the smaller signals from the brain, where a sensitivity of at least $10 fTHz^{-1/2}$ is preferable; however, we have already observed sufficiently low levels of noise in unpatterned films grown by laser ablation,[14] thus demonstrating that such levels of performance are, in principle, obtainable.

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