Improving the AC Sensitivity of an HTS SQUID using a Cooled LC Circuit

Longqing Qiu[(1,2)], Yi Zhang[(1)], Hans-Joachim Krause[(1)] and Alex I. Braginski[(1)]

(1)Institut für Bio- und Nanosysteme, Forschungszentrum Jülich GmbH, *D-52425*Jülich, Germany*;* e-mail: l.qiu@fz-juelich.de
(2)Pohl Institute of Solid State Physics, Tongji University, Shanghai 200092, China

***Abstract* - A single-coil *LC* resonant circuit has been used for improving the alternating-current (ac) magnetic field resolution of a high-temperature superconductor SQUID at a distinct frequency,. The inductor *L* acts as both a pickup coil and an input coil. Within the liquid nitrogen bath, the coil surrounds the SQUID and couples to it inductively. Copper coils with different number of windings were used to cover the frequency range from < 1 to nearly 100 kHz. A superconducting coil made of $YBa_2Cu_3O_{7-\delta}$ (YBCO) tape conductor was also tested. With the *LC* circuit, the signal-to-noise ratio of measurements could be improved typically by one order of magnitude or more in a narrow frequency band around the resonance frequency exceeding a few kHz. The best attained equivalent magnetic field resolution was 2.5 fT/√Hz at 88 kHz.**

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I. INTRODUCTION

In some applications of superconducting quantum interference devices (SQUIDs), a high magnetic field sensitivity is needed only at a distinct frequency. In the case of low-temperature superconducting (LTS) SQUIDs, a resonant sensitivity enhancement may easily be realized using a resonant flux transformer, consisting of a pickup coil wound from niobium wire and a capacitor [1]. In the case of HTS devices, however, only planar structures have been used to date, because flexible, bondable high-T_c wire of sufficient quality is not available yet.

It has been shown that resonant transformers made of normal conducting wires could improve the sensitivity of a SQUID from several kHz to about 1 MHz [2,3].

We reported recently on a new design of resonant-type coupling circuit suitable for high-T_c SQUID [4]. This note is a short version of [4]. Our *LC* circuit consists of only one coil which acts as both a pickup coil and an input coil. The coil surrounds the HTS SQUID within the liquid nitrogen bath and is shunted by a capacitor.

II. THE *LC* CIRCUIT GAIN AND NOISE

A. Equivalent Circuit and Analysis

The equivalent circuit of the SQUID with the cooled *LC* circuit and the experimental arrangement in the cryostat are sketched in Figs. 1 (a) and (b), respectively. The SQUID is located in the center of the coil of the *LC* circuit. Both the SQUID and the coil are situated in liquid nitrogen in a cryostat.

The signal gain was calculated, taking into account the parameters of the circuit, the inductance *L*, the resistance *R* and the total capacitance *C*, consisting of shunt capacitance and parasitic capacitance of the coil. The expected gain increases with frequency and with the number of turns of the coil. Unfortunately, the *LC* circuit contributes also an additional flux noise to the SQUID. Only if the signal gain is larger than the noise gain, the circuit improves the signal-to-noise ratio (SNR) of the measurement. Details of the analysis can be found in [4].

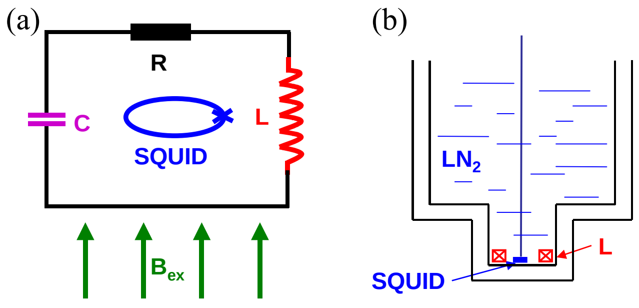

Fig. 1. Equivalent circuit (a) and schematic diagram (b) of the *LC*-circuit-assisted SQUID inside the liquid nitrogen bath.

B. Results with Normal Coils

The analysis was experimentally verified with a radio frequency (rf) SQUID-magnetometer of the so-called substrate resonator type [5]. The SQUID magnetometer as such achieved a field resolution of about 40 fT/√Hz in shielded environment.

The SQUID was positioned in the center of an *LC* circuit. An AC magnetic field at $f = 39.2$ kHz (the resonant frequency of the circuit) was applied to the SQUID. The red curve in Fig. 2 shows the measured noise (and signal) density spectrum of the SQUID output with the *LC* circuit in place. For comparison, the blue curve shows the spectrum after removal of the *LC* circuit. In this case, the signal gain reached 32, while the noise gain was 3.1 only. Thus we got an SNR improvement of 10.3.

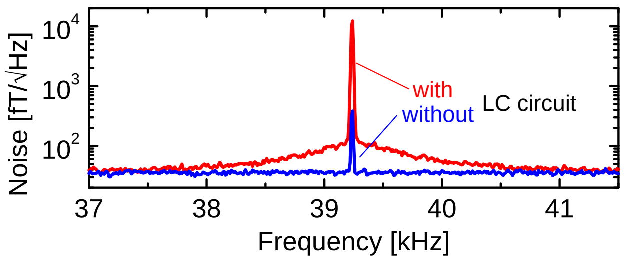

Fig. 2. Measured magnetic field noise density spectra without (blue) and with (red) *LC* circuit. Without the *LC* circuit, the signal and noise were 384 fT and 35 fT/√Hz, respectively; with the *LC* circuit, the signal and noise were 12.3 pT and 108 fT/√Hz, respectively.

Several coils with different numbers of turns of enameled copper wire were investigated. Each coil was successively shunted with different capacitors, thus obtaining a wide range of resonance frequencies. At each resonance frequency, spectral noise measurements were performed and both the signal gain and the noise gain were extracted. Figure 3 depicts the resultant total gain (SNGR). Each point corresponds to a different capacitance value; data for coils with different turn numbers are marked by different colors. The maximum gain obtained with the optimum coil-capacitor pair is sketched in the inset. The best measured gains ranged from about 10 at 10 kHz to 16 at 88 kHz. The lowest equivalent magnetic field resolution was 2.5 fT/√Hz at 88 kHz.

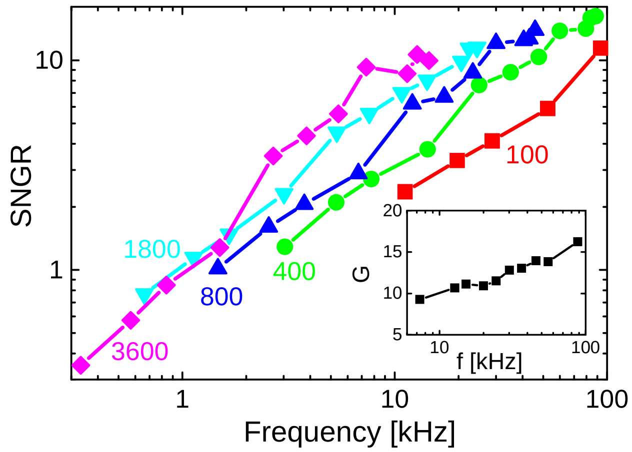

Fig. 3. SNGR of *LC* circuits with coils of different windings and different shunt capacitors, measured at their respective resonance. The inset displays the maximum gain *G* obtained with the circuit working best at each frequency.

C. Results wit a Superconducting Coil

Additionally, one superconducting coil was also tested. The 49-turn coil was wound from a 4 mm wide tape of YBCO superconductor, deposited on 100 µm thick stainless steel substrate, with a 100 µm thick interlayer insulation tape. This coil had a mean diameter of 37 mm and an inductance of 90 µH. It was fabricated by European High Temperature Superconductors GmbH & Co. KG (EHTS). Figure 4 depicts the SGNR measured with this coil (blue). The optimum gains obtained with individually optimized normal conducting coils are graphed in red. For comparison, the performance of one copper coil with the same inductance as the superconducting coil is plotted in green.

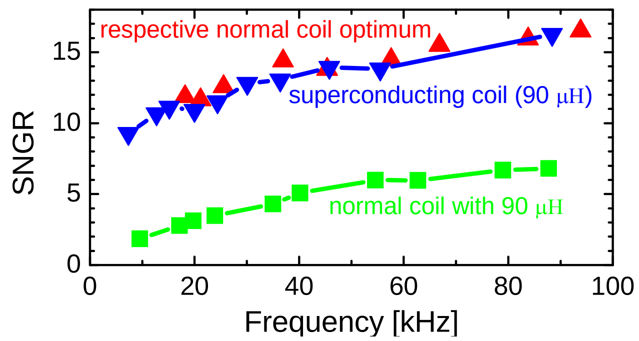

Fig. 4. Measured *SNGR* of normal and superconducting coil circuits: blue – superconducting coil, red – maximum *SNGR* of different normal coils at their respective optimum, green – normal coil with same inductance as superconducting coil.

IV. CONCLUSION AND OUTLOOK

It was shown that simple *LC* circuits improve the SNR of HTS SQUID measurements very effectively at a distinct frequency. Above 10 kHz, magnetic field resolutions below 4 fT/√Hz were attained, reaching 2.5 fT/√Hz at 88 kHz. The test of one low inductance superconducting tape coil resulted in SNR improvement equivalent to that attained with a whole set of normal coils having much higher inductances. Further improvement is attainable by optimizing the tape conductor: a significant increase of the number of coil turns via thinner tape substrate and thinner interlayer insulation is expected to yield even higher gains, albeit at the expense of reduced bandwidth.

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