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# Observation of rf SQUID characteristics in YBCO bulk at 77 K

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**Abstract.** RF SQUID behaviour due to grain boundary weak links in a bulk YBCO is observed at 77 K using modified commercial rf electronics. Porous samples with low $I_c$ are found to show this characteristic whereas dense samples with higher $I_c$ do not show SQUID behaviour. $V$-$B$ modulation characteristic is found to be better when the rf pumping frequency is kept slightly higher than the resonance frequency of the tank circuit. Designing of coil for tank circuit with appropriate $Q$ has been found to be very crucial for seeing the SQUID behaviour. Estimation of parameters such as coupling constant, mutual inductance, inductance and radius of the SQUID loop, have been made and their significance is discussed. Flux noise spectrum of the bulk rf SQUID in flux locked mode is also reported.

**Keywords.** High $T_c$ superconductors; rf SQUIDs; granular superconductors.

**PACS No.** 74·70

## 1. Introduction

High $T_c$ oxide superconductors are granular in nature and superconducting grains are weakly connected at the grain boundary. These grain boundary weak links work as Josephson junctions (Gupta *et al* 1987). The possibility of using these grain boundary weak links in a ring of a bulk superconductor to fabricate an rf SQUID was realized during first measurement of flux quantum (Gough *et al* 1987; Colclough *et al* 1987). It was later demonstrated that even the superconducting loops between grains could give rise to rf SQUID behaviour in high $T_c$ bulk samples (Pegrum *et al* 1987; Tichy *et al* 1988). In this paper we report the observation of rf SQUID behaviour at 77 K in YBCO bulk superconductor. The effect of $Q$ of the tank coil and quality of the sample on rf SQUID behaviour are discussed. An estimate of various SQUID parameters has been made which provides insight into the observed rf SQUID behaviour.

## 2. Experimental

YBCO samples are prepared by the standard solid state reaction technique using $Y_2O_3$, $BaCO_3$ and CuO of 99·9% purity. Different quality of pellets has been prepared by varying the pelletizing pressures before sintering. For realizing the rf SQUID behaviour in bulk YBCO, a rectangular shaped sample is cut from the superconducting YBCO pellet. Commercial rf SQUID electronics used for conventional niobium rf

SQUID has been found unsuitable for observing SQUID behaviour in high $T_c$ superconductors. Its inbuilt rf oscillator has maximum output voltage $\sim 100\,\mu V$ which is quite low. The overall gain of the amplifier is 83 dB which is large enough to limit the dynamic range of the detection circuit. As a result even slightly large rf voltage at the tank circuit causes saturation of the detector output. For using the commercial electronics in the present experiment, its internal rf source is disabled and an external rf oscillator (HP 3325 B) is connected. Frequency and amplitude of the rf oscillator can be thus varied over a wide range. Gain of the amplifier has been decreased by modifying the amplifier circuit. It is reduced from 83 dB to 60 dB. This increases the dynamic range of the detection circuit. Ten turns of copper wire are wound around the sample to form the coil of the tank circuit which is connected in parallel to a capacitor. At 77 K its resonance frequency was 19·13 MHz while its $Q$ was 42. For applying the magnetic field a solenoid is made to surround the sample. The solenoidal coil is 8 mm dia and 20 mm long and produces a dc field of $1{\cdot}2 \times 10^{-3}$ TA$^{-1}$. An external *af* oscillator (Wavetek Model 166) is connected to the solenoidal coil for producing ac magnetic field. Figure 1 shows the schematic diagram of the experimental set up for observing the rf SQUID characteristic of the bulk YBCO. RF oscillator is used to feed the signal to the tank circuit. The reflected rf signal is amplified using a low noise amplifier and is detected using a diode detector. For recording *V-B* characteristic of the SQUID, the detector output of the electronics is fed to $Y$ channel of CRO while the output of *af* oscillator is connected to the $X$ channel. Three layers of $\mu$-metal surrounding the sample is used for magnetic shielding. In addition to $\mu$-metal shield, a high $T_c$ superconducting YBCO tube is also used as an additional shield. Flux noise spectrum of the bulk SQUID is studied using lock-in technique (Keene *et al* 1990). Figure 2 shows the schematic diagram of the experimental set up for measuring voltage noise spectrum, $S_v(f)$. Current in the coil for producing the magnetic field is reduced so that $I(\text{coil}) < I_{\Phi_0}/4$, where $I_{\Phi_0}$ is the current in the drive coil to change the flux in the SQUID by one quantum. The detector output is connected to the lock-in amplifier whose reference signal is coming from an *af* oscillator. Output of the lock-in amplifier is fed to another lock-in amplifier for recording voltage noise spectrum, $S_v(f)$ (Maeda *et al* 1989). Noise measurement is done using lock-in amplifier in *ac* voltmeter mode. In this mode, the rms of the

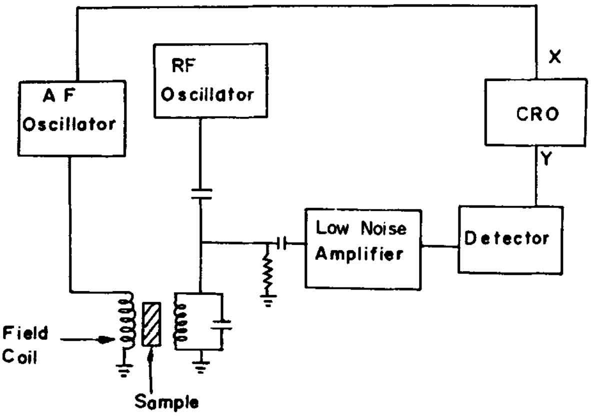

Figure 1. Schematic diagram of the experimental set up for observing rf SQUID characteristic in bulk YBCO.

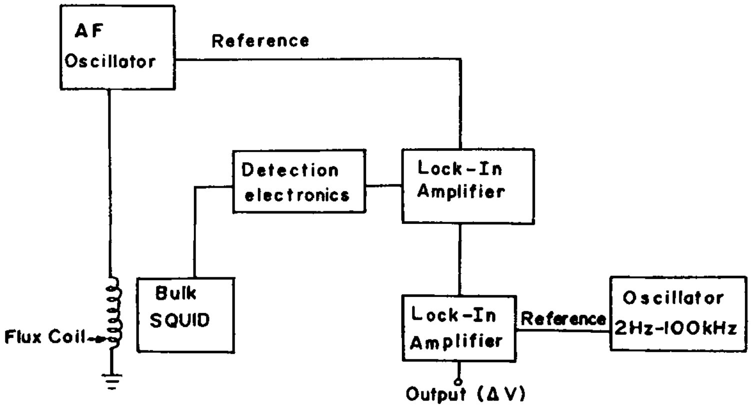

**Figure 2.** Schematic diagram of the experimental set up for measuring voltage noise spectrum of the rf bulk SQUID.

fluctuating voltage, $\Delta v$, is measured at a fixed frequency $f$ with a constant $Q$ value, which is typically 100. Thus, the $S_v(f)$, voltage noise spectrum is obtained by the formula, $S_v(f)=(\Delta v)^2\ (Q/f)$. The flux noise density can thus be calculated as $[S_\Phi(f)]^{\frac{1}{2}} = [S_v(f)/(\partial v/\partial \Phi)^2]^{\frac{1}{2}}$ where $\partial v/\partial \Phi$ is the transfer function of the $V$-$B$ characteristic of the bulk YBCO SQUID.

## 3. Results and discussion

Figure 3 shows the $V$-$B$ characteristics of YBCO bulk at two different rf frequencies. Curve b at 19·13 MHz which happens to be the resonance frequency of the tank circuit and the curve a at a frequency slightly higher than the resonance frequency. $V$-$B$ response is similar to a typical rf SQUID characteristic. Good triangular response (curve a) is observed at rf frequency of 19·30 MHz which is slightly larger than the resonance frequency of the tank circuit at 77 K. The amplitude of the observed triangular characteristic is found to be sensitive to the rf pumping voltages ($V_T$). At $V_T = 8$ mV better resolved triangular patterns are observed whereas at lower or higher rf voltages the patterns get blurred and their amplitude diminishes. These turn noisy and finally disappear. RF SQUID characteristics have been observed in porous pellets of YBCO. These pellets have relatively poor $I_c$. Dense samples with higher critical currents do not show triangular response in $V$-$B$ characteristic.

Observation of rf SQUID characteristic in the bulk YBCO insures that for the present case thermal noise of the device at measurement temperature is appreciably less than the magnetic energy due to the flux, i.e. $\Phi_0^2/2L_{SQ} \gg k_B T$ where $\Phi_0$ is the flux quantum and $L_{SQ}$ is the inductance of the SQUID loop. This expression can give some estimate of the $L_{SQ}$. At 77 K, $L_{SQ} < 4 \times 10^{-9}$ H. A better estimate of this parameter can be obtained considering the geometrical relations. The geometrical inductance $L$ of a simple circular loop of radius $R$ is given by the expression $L = \mu_0 \pi R/2$, where permeability $\mu_0 = 4\pi \times 10^{-7}$ H/m. This gives $L_{SQ} \sim 1{\cdot}97 \times 10^{-6}$ R. The coupling constant, $k$, can be approximately given as the ratio of the effective area of the cross section of the rf coil and of the coupled SQUID loop. For the dimensions of our rf coil we obtain $k \sim 4 \times 10^6\,\mathrm{R}^2$.

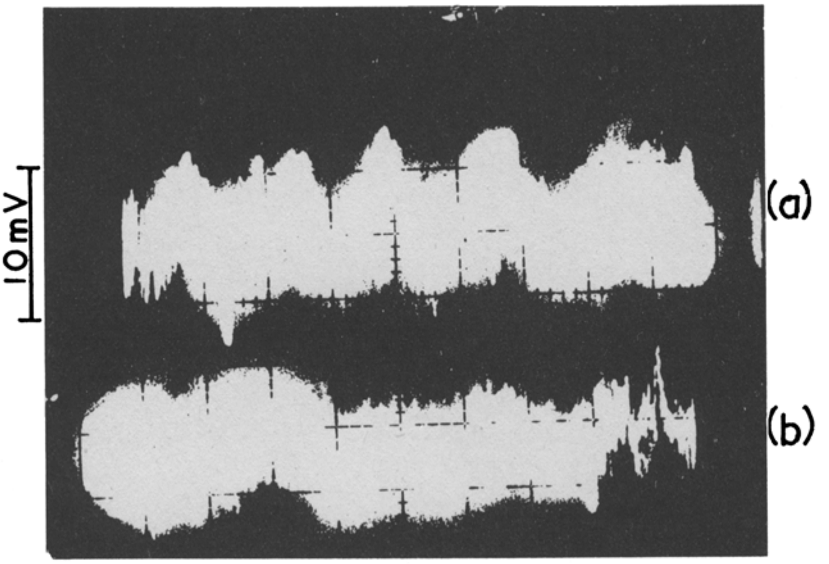

**Figure 3.** RF SQUID response of bulk YBCO samples at 77 K for two rf frequencies (**a**) $f = 19{\cdot}30$ MHz (**b**) $f = 19{\cdot}13$ MHz (resonance frequency).

The mutual inductance $M$ between the SQUID loop and external deriving coil can be measured directly by simply determining the drive coil current, $I_{\Phi_0}$ required to change the SQUID flux by one $\Phi_0$ thus $M = \Phi_0/I_{\Phi_0}$. For the present case $I_{\Phi_0} = 1{\cdot}2 \times 10^{-3}$ A which gives $M = 1{\cdot}7 \times 10^{-12}$ H. The mutual inductance can also be expressed by the relation, $M = k\sqrt{L_T L_{SQ}}$ where $L_T$ is the inductance of the tank circuit and $k$ is the coupling constant. $L_T$ can be directly measured. So the measured $M/\sqrt{L_T} \sim k\sqrt{L_{SQ}} \sim 5{\cdot}9 \times 10^{-9}$. Also $k\sqrt{L_{SQ}} \sim 5{\cdot}61 \times 10^3 R^{5/2}$. Thus we can estimate radius of the SQUID loop as $R \sim 16{\cdot}2\,\mu$m and area of the loop $A \sim 8{\cdot}24 \times 10^{-10}\,\mathrm{m}^2$. Substituting the value of $R$ in the expressions for coupling constant and SQUID inductance yields $k \sim 10{\cdot}5 \times 10^{-4}$ and $L_{SQ} \sim 3{\cdot}2 \times 10^{-11}$ H. $Q$ of the tank circuit in the present case was 42. Thus $k^2Q \sim 4{\cdot}6 \times 10^{-5}$ which is much smaller than the ideal condition $k^2Q \sim 1$. Smaller value of $k^2Q$ is responsible for lack of resolution of the triangular patterns. Since the value of $k$ is very small, choice of $Q$ becomes very crucial. If the coil is not designed suitably so that $Q > 30$ then no triangular modulation pattern can be observed. Smaller value of $Q$ makes $k^2Q$ more small which hampers resolution in rf SQUID characteristics. The observed low value of the coupling constant, $k$ may be due to formation of SQUID loop somewhere inside the bulk sample and moreover the SQUID loop may not be in the same plane to the driving coil.

When the rf voltage at the tank circuit was 8 mV better $V$-$B$ characteristic with well defined triangular patterns was observed whereas for voltages lower than this gave no triangular patterns in $V$-$B$ characteristics. This $V_T = 8$ mV can be considered as the rf voltage corresponding to the first step in the $V_{rf} - I_{rf}$ characteristic. Thus $V_T$ can be expressed as $L_T L_{SQ} I_c \omega/M$ where $I_c$ is the critical current of the grain boundary Josephson junction. Substituting the values of $L_T$, $L_{SQ}$, $V_T$, $M$ and $\omega$ gives $I_c \sim 41\,\mu A$ which is a reasonable value.

The hysteresis parameter $\beta$ is given by $2\pi\, I_c L_{SQ}/\Phi_0$ which comes out to be 4·2. The noise parameter $\gamma = 2\pi k_B T/\Phi_0 I_c$ for $T = 77$ K is equal to $7{\cdot}9 \times 10^{-2}$. It is known

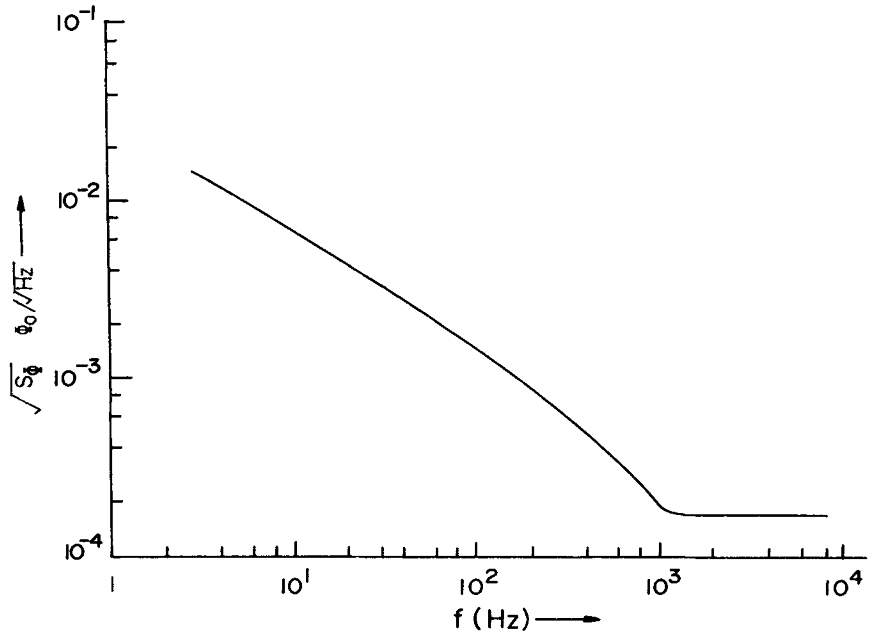

**Figure 4.** Flux noise density spectrum of the bulk YBCO SQUID at 77 K.

that for the correct function of the hysteric rf interferometers one must fulfil the condition $\gamma^{2/3}\ \beta \ll 2$ (Tichy *et al* 1988). In our case this value is about 0·75 which clearly satisfy the above criterion.

Figure 4 shows the noise spectrum of the bulk SQUID. For frequencies > 1 kHz, $\sqrt{S_\Phi}$ was $2 \times 10^{-4}\ \Phi_0/\sqrt{\mathrm{Hz}}$ and it remains constant. For these range of frequencies. bulk SQUID is only two times more noisy than the commercial rf niobium SQUID. However, at lower frequencies ($f < 1$ kHz), $\sqrt{S_\Phi}$ was found to increase due to the intrinsic $1/f$ noise. This arises most probably due to thermal activation of the trapped flux. More noise observed in the present case partly owes to the poor quality of the sample. The circumference of the SQUID loop forming inside the bulk ~ 100 μm, whereas the grain size in the material is ~ 5–10 μm. Thus the superconducting loop contains several grain boundary junctions with assorted critical currents. The presence of dissimilar grain boundary weak links causes more noise.

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