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NARROW-BAND ULTRA-LOW CURRENT MEASUREMENTS WITH A RF SQUID

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Résumé.- L'utilisation d'un transformateur à noyau ferromagnétique couplé à un SQUID permet de mesurer de très faibles courants, comme nous l'avons précédemment montré. L'utilisation d'un noyau céramique à faible pertes pour le transformateur a permis d'augmenter ultérieurement la sensibilité de presque deux ordres de grandeur dans une bande étroite autour d'une fréquence donnée. Actuellement on obtient une sensibilité de presque 8×10^{-4} pA dans une largeur de bande de 1 Hz à 150 Hz.

Abstract.- The use of a ferromagnetic transformer coupled to a SQUID, as previously described, permits to measure very low currents. A low loss ceramic core for the transformer has yielded to further increase in the sensitivity of about two orders of magnitude in a narrow-band around a fixed frequency. At present the achieved sensitivity of about 8×10^{-4} pA in 1 Hz bandwidth at 150 Hz.

The use of a superconducting magnetometer as a high sensitivity current detector has been proposed by some authors a few years ago [1,2,3]. More recently, by coupling a transformer with a ferromagnetic core to a rf SQUID [4], we have enhanced the overall current sensitivity up to very interesting figures [5]. Due to the particular ferromagnetic material employed [6] the useful bandwidth of the device was constrained between dc and a corner frequency dictated by the strong frequency dependence of the relative permeability of the used core. In order to enhance the current sensitivity at a fixed frequency we inserted a tuning capacitor in the input circuit. However, due to the high value of the electrical conductivity of the core a large amount of eddy-current losses was present, limiting the Q of the urned circuit to not interesting values. This drawback has been overcome by means of a suitable choice of a ceramic core for the transformer. We have tested a few commercially available ferrites in order to select those which preserve an acceptable value of the relative permeability at liquid helium temperature. The chosen material has been used to make up a superconducting transformer coupled to the SQUID as shown in figure 1. The current I (v) is supplied by a current generator I to the input circuit which consists of a capacitance C paralleled to the primary L_T (N_T turns) of the transformer. The secondary winding L_P (N_P turns) is connected with the inductance L_S to obtain as usual a flux transformer. All windings are made of superconducting wire. $M_{TP} = K_{TP}\sqrt{L_T L_P}$ is the mutual inductance between L_T and L_P , while $M = K\sqrt{L_S L}$ is the

mutual inductance between L_S and the inductance of the SQUID, L .

Fig. 1 : Schematic of the experimental arrangement used for narrow-band ultra-low current measurements. The room temperature current generator I feeds the "tuned" input circuit C, L_T : L_T and L_P are wound over the ferromagnetic core. All inductances L_T , L_P and L_S are made up with superconducting wire. For other symbols meaning see text.

A straightforward analysis [5] of the circuit of figure 1 shows that, once the matching condition for the flux transformer is satisfied, i.e. $L_P \approx L_S$ "in situ", the current sensitivity of the device is enhanced by a factor $\approx \frac{N_T K_{TP}}{2 N_P}$ below the resonance frequency. At resonance a further gain is obtained, given by the factor of merit Q of the input circuit.

A typical experimental result obtained with this technique is shown in figure 2, where the input current i° (v), which causes the SQUID to slip one flux quantum, is reported versus frequency. Data are taken with the following set of experimental parameters: C : 0.312 μ F, $N_T = 8360$, $N_P = 6$, $K_{TP} = 0.95$, $L_S = 10.5$ μ H.

All superconducting coils have been wound using a 50 μ m formwar insulated Nb wire. One

One Phillips "potcore" Ferroxcube 3B2 grade has been used for the transformer : geometrical dimensions of the core obviously constrained the maximum number of turns for the primary winding L_T .

Fig. 2 : (*) : experimental behavior i^0_{rms} versus frequency ; i^0 is the current which, flowing in the input "tuned" circuit causes the SQUID to slip one flux quantum. Experimental values of the relevant parameters are : $N_T = 8360$, $N_P = 6$, $L_S = 10.5 \mu H$, $L = 4.2 \times 10^{-10} H$, $K_{TP} = 0.95$, $M = 5.75 \times 10^{-8} H$ and $C = 0.312 \mu F$. (Δ) : measured root-mean square flux noise values in units of Φ_0 per $Hz^{1/2}$ versus frequency.

A two-hole symmetric SQUID ($L = 4.2 \times 10^{-10} H$) has been used to obtain a value for M as large as possible. With the value of the inductance L_S mentioned above we achieved experimental value for the mutual inductance $M = 5.75 \times 10^{-8} H$. The measured value of $i^0 \sim 22 pA/\Phi_0$ at frequencies below resonance well agrees with the calculated value $i^0_c \sim \frac{\Phi_0}{2} \frac{N_P}{M K_{TP} N_T} \sim 20 pA/\Phi_0$. It is evident from data figure 2 that an improvement in current sensitivity of about two orders of magnitude at a fixed frequency is obtained by means of resonance.

As the ultimate performances of the system are determined by the signal to noise ratio, it is important to know the output noise spectrum. In figure 2 we also report the measured output noise expressed in flux quantum units per $\sqrt{Hz}$ versus frequency. Noise measurements have been performed sending the "linearized" SQUID output to a lock-in used as a narrow-band amplifier, the output of which is suc-

cessively squared and integrated. Data show that the output noise is moderately dependent on the frequency : its value, at resonance, is only about one order of magnitude larger than the value obtainable with the SQUID not coupled to a transformer. This means that, at the resonance frequency, the minimum detectable current, in 1 Hz bandwidth, is $i_{min} \sim 0.8 \times 10^{-15} A$.

The sensitivity of the device is limited by the relatively low value of the factor of merit of the input circuit ($Q \sim 85$). This drawback doesn't seem due to losses in the ferrite core. The properties of the ceramic core as given by factory's specifications should yield to a Q several order of magnitude larger than the measured one. Moreover the small Q -value cannot be due to losses in the capacitance, because of the above mentioned behavior of the noise versus frequency. We believe that the limitations to the resonant gain in the input circuit may be justified as due to an input dissipative term of the SQUID, which should be reported into the input circuit, increased by a factor $\sim N^2$. The authors are indebted to Prof. R.P. Giffard for useful discussions.

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