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Optimization of high-Q low frequency NMR measurement

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In low temperature applications high-Q resonance circuits can be constructed for low frequencies. With a superconducting coil a Q $\sim 10^4$ is obtainable if it is connected directly to a preamplifier at low temperatures. We discuss the optimization of the resonance circuit and preamplifier for NMR at 0.1 – 1 MHz.

1. INTRODUCTION

In low temperature measurement noise is often dominated by pick-up from external interference in the long connection to room temperature and not by noise in the detector or the preamplifier. We use a superconducting pick-up coil coupled to a low temperature GaAs FET preamplifier for cw NMR on superfluid ^{3}He. [1] The tank circuit has a Q $\sim$ 2000 and the preamplifier a wide-band gain $G \sim 10$, with an input reduced noise voltage of < 10 nV/$\sqrt{\text{Hz}}$. Nevertheless, the noise level in the NMR signal measured from the cryostat is an order of magnitude larger due to interference. One solution to boost the signal-to-noise ratio is to increase the overall gain of the low temperature circuit. We discuss here two improvements in this respect: 1) How to increase the Q-value of the pick-up coil which is limited by eddy current losses. 2) How to increase the gain of the preamplifier and to reduce its output impedance with passive elements such that the power consumption remains less than 50 mW.

2. RESONANCE CIRCUIT

A small superconducting pick-up coil of solenoidal shape, with a single layer of 25 μm diameter Nb wire, may have a Q as large as $(2-5)\cdot 10^4$. [1] Filamentary NbTi wire in a CuNi matrix of 50 μm diameter, which is easier to handle, also gives comparable high Q values. In practice, when the coil is placed in our NMR measuring set-up the Q is found to be reduced to $2 \cdot 10^3$. The discrepancy has been traced to RF losses in the cylindrical phosphor-bronze coil former of the steady field NMR magnet, as confirmed by the measurements shown in Table 1.

Cylinder	Q	$1/Q - 1/Q_0 \times 10^6$
none	$15200 = Q_0$	-
annealed copper	14670	2
machined copper	8560	50
bronze	6290	90
brass	4360	160

Table 1: Q of a resonance circuit consisting of a solenoidal coil in the center of various metal cylinders. The RF losses are expressed as $1/Q - 1/Q_0$. The changes in Q are large while the corresponding decreases in frequency are only of order 0.2 %. The cylinders have a length = 50 mm, i. d. = 30 mm, and o. d. = 32 mm. The coil has 200 turns of 50 μm filamentary NbTi wire in a CuNi matrix, wound in 2 layers with diameter = length = 6 mm and inductance $L = 160\,\mu$H. It is resonated at 4.2 K and 400 kHz with a parallel high-Q ceramic capacitance from American Technical Ceramics Corporation (Huntington Station, N.Y. 11746-2102, USA; series 100 or 175).

According to these results, a large increase in the Q is expected by inserting an annealed high-conductivity copper cylinder between the pick-up coil and the poorly conducting magnet body.

3. PREAMPLIFIER

Our low temperature preamplifier [1] in Fig. 1a is located inside the vacuum jacket with thermalization to 4 K. It operates with two GaAs dual-gate FETs in cascode (Sony 3SK166 N-channel MESFET). With a load resistor $R_L = 500\ \Omega$ the gain $G \approx 6$ is flat up to 900 kHz. For narrow-band application the gain can be increased and the power consumption at 4 K reduced by replacing R_L with a tuned output circuit (Q $\approx$ 10), as shown in Fig. 1b. The gain is then 20 times larger and the output impedance

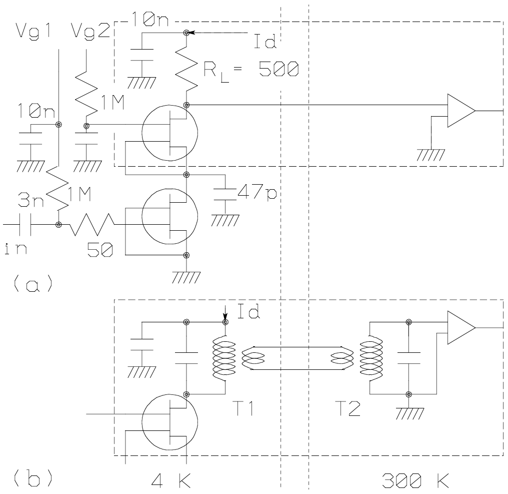

Figure 1: (a) Wide-band amplifier. (b) Load resistor R_L replaced with a tuned output circuit. The identical transformers T1 and T2 are wound on toroidal sintered iron powder cores (Amidon Associates, Torrance, CA 90508-956, USA; type T37-15). The primary consists of 100 turns of 0.1 mm Cu wire. The secondary is 10 turns.

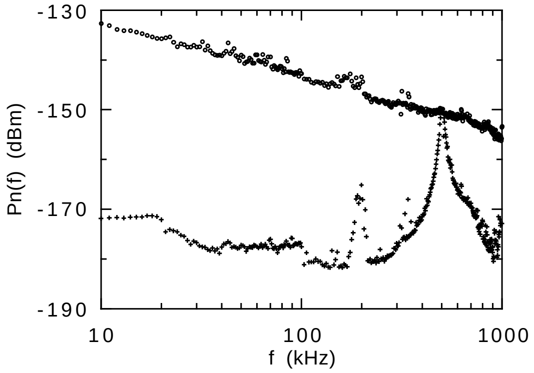

Figure 2: Spectra of input reduced noise power density $P_n(f)$ of wide and narrow-band output designs. The bias settings are the same as in Table 2.

seen by the room temperature circuitry is reduced. The transformer coupling disconnects the low temperature electronics galvanically from the later stages providing better immunity to grounding problems.

Table 2 compares the measured voltage gains G of the two designs in Fig. 1. Fig. 2 shows the input reduced spectrum of the noise power density per Hz $P_n(f) = 20\ \log_{10}(V_n(f)/0.316)$, where $V_n(f)$ is the input reduced noise voltage amplitude at the frequency f in Volts. $P_n(f)$ is measured with the preamplifier input shorted with a 50 Ω resistor. The 1/f noise is seen to extend to above 1 MHz in the wide-band output. This is reasonable since the GaAs FETs are designed for UHF use.[2] With the narrow-banded output $P_n(f)$ is effectively 40 dB smaller except at the 500 kHz band-pass point where the two designs have equal $P_n(f)$. This means that at 500 kHz the noise, when reduced to the input, has remained unchanged. When the FETs are turned off, the wide-band $P_n(f)$ is reduced by 5 dB whereas the reduction of the narrow-band output is 15 dB at 500 kHz. Thus in the latter case there is an improvement by 10 dB in the noise which is added into the circuit after the FETs, mainly in the long cable to room temperature.

amp	400	500	600	700	800	(kHz)
wide	7	7	6	6	5	
narrow	13	160	22	18	8	

Table 2: Wide and narrow-band amplifier gain as a function of frequency. The drain current is I_d = 8.5 mA (5.0 mA), the bias voltages are V_{g1} = -1.08 V (-1.2 V) and V_{g2} = 0.93 V (0.93 V) for the wide-band (narrow-band) amplifier.

The wide-band preamplifier has been used for NMR on superfluid ^{3}He in a rotating cryostat which is operated on compressed air bearings and where interference effects due grounding problems are exceptionally severe. Single-vortex-line resolution has been achieved in ^{3}He-B but not in ^{3}He-A. [3]. With an increased Q value in the resonance circuit, reduced sensitivity to noise pick-up due to the narrow-band design, and increased gain we expect to achieve an order of magnitude improvement in the signal-to-noise ratio.

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