A 200 $\hbar$ two-stage dc SQUID amplifier for resonant gravitational wave detectors

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Abstract
Starting from commercial chips a two-stage dc Superconducting Quantum Interference Device (SQUID) was developed in order to be used as low noise amplifier on the resonant gravitational wave detector AURIGA. The SQUID was coupled to a high Q electrical resonator, operating in the kHz frequency range, which was employed to simulate the real detector. The resonator was successfully stabilized by means of a capacitive damping network. SQUID additive noise and back action noise were measured as function of temperature. The best noise temperature of the SQUID amplifier, measured at 1.5 K, was better than 16 μK, and correspond to minimum detectable energy of 200 resonator quanta.

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1. Introduction

Most resonant gravitational wave (GW) detectors use a dc Superconducting Quantum Interference Device (SQUID) as low noise amplifier. In these detectors the minimum detectable energy is given by [1]:

$$E_{\min} = k_{\mathrm{B}} T_{\mathrm{n}} = \frac{1}{2}\sqrt{S_{vv} S_{ii} - \mathrm{Im}(S_{iv})^2} \tag{1}$$

T_{n} is the noise temperature, k_{B} is the Boltzmann's constant, S_{vv}, S_{ii} and S_{iv} are the monolateral power spectral densities and the cross-correlation spectral density of the voltage and current noise sources, V_{n} and I_{n}, of the SQUID modeled as current amplifier (Fig. 1(a)). Another figure of merit commonly used for SQUIDs is the energy resolution, $e=S_{ii}\times(L_{\mathrm{i}}/2)$, where L_{i} is the SQUID input coil inductance. Up to now, the best result of a SQUID coupled to a GW detector was obtained in the AURIGA experiment, where a commercial SQUID was operated with e=4000 $\hbar$ [2]. However near-quantum-limited SQUIDs with an uncoupled energy resolution of a few $\hbar$ have been described in literature [3], which could in principle improve the sensitivity of the operating detectors by more than two order of magnitude. Thus a crucial step, not yet fulfilled, is to demonstrate that a low noise dc SQUID can be operated on a resonant GW detector without significant increase in the noise.

In this paper we present an amplifier, based on a two-stage SQUID, that we plan to use in the next run of the resonant GW detector AURIGA [4]. We have coupled the SQUID to a high *Q* electrical resonator, operating in the kHz frequency range, which is employed as simulator of the high *Q* input load of a resonant GW detector. The advantage of this system is that it allows performing significant cryogenic tests within a thermal time much shorter than that of the GW detector (1 hour compared to 1 month).

We have identified and solved the two main problems related to the use of a SQUID with a high *Q* resonant input load: the effect of the resonances at the Josephson frequency in the low loss input load and the possible instabilities of the system due to a negative real part of the dynamic input impedance of the SQUID [5]. Finally we have characterized the noise sources and set an upper limit on the true noise temperature of the SQUID amplifier in the temperature range 1.5 - 4.2 K.

2. Experimental apparatus

The circuit, composed of the resonator coupled to the two-stage dc SQUID amplifier, is shown in Fig. 1(b).

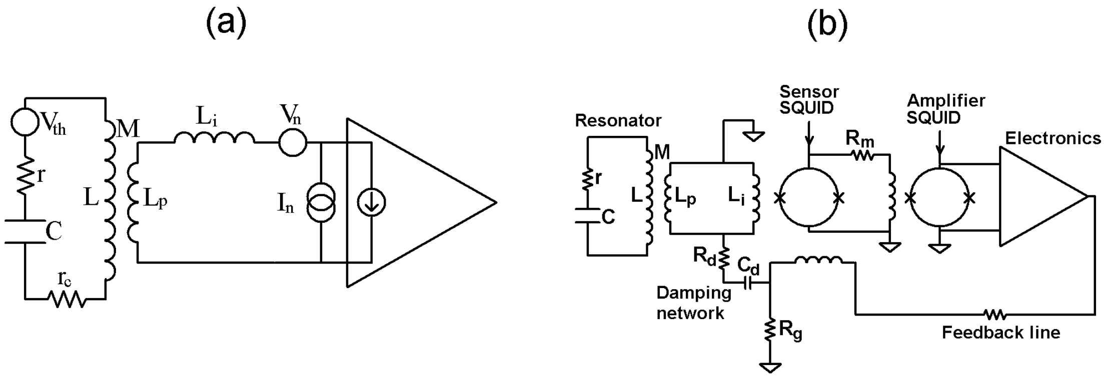

Figure 1. (a) Noise model of the SQUID coupled to the high *Q* electrical resonator. (b) Schematic circuit of the two-stage SQUID coupled to the high *Q* electrical resonator.

In a two-stage system a second SQUID (the amplifier) is used as a low noise preamplifier of the first (the sensor). Both sensor and amplifier chips were manufactured by Quantum Design [6]. Josephson junctions shunt resistances and loop inductance of both SQUIDs are respectively R_S=2 Ω and L_S=80 pH. The SQUIDs are placed in different shields and are connected to the room temperature electronics through different cables in order to avoid any stray crosstalk between the wires. The sensor SQUID, biased through a battery-powered current box, is not modulated and its output voltage is fed through a matching resistor R_m=2.2 Ω to the amplifier SQUID, that is finally read out by standard manufacturer electronics with a 500 kHz modulation scheme. The system is operated in conventional flux locked loop, with the output signal from the amplifier SQUID electronics sent to a 1-pole integrator and fed back to the sensor SQUID. The maximum bandwidth of the system in closed loop mode is limited by various filtering stages to about 50 kHz. The slew rate is about 2×10^4 ϕ_0/s.

The high Q resonator is based on a low-loss and low-stray-capacitance superconducting coil with inductance (in its housing) L=0.55 H and a Teflon capacitor C=19.1 nF. The SQUID is coupled to the resonator by means of a superconducting flux transformer whose elements are the SQUID input coil L_i=1.64 μH and the pick-up coil L_p=2.8 μH. The coupling factor between the pick-up coil and the resonator coil is $k=M/(LL_p)^{1/2}\cong0.5$. The effective inductance of the resonator coil is reduced by the coupling to the flux transformer to the value L_r=0.475 H. The resonance frequency is $n_0=w_0/(2\pi)$=1671.4 Hz and the intrinsic quality factor at is $Q_{int}=1.08\times10^6$.

Other experimental details of the two-stage SQUID [7] and of the resonator and its housing [8] are reported in previous works.

3. Optimization and stabilization of the system

When the SQUID is strongly coupled to the low loss resonator coil a strong degradation of the SQUID characteristics is usually observed. This effect is probably due to the fact that the SQUID interacts at Josephson frequency with some high frequency resonances in the low loss input load [9]. This hypothesis is supported by the fact that the degradation is suppressed by grounding the input transformer, as shown in Fig. 1(b). In fact in this configuration the Josephson signals generated by the SQUID, which would be normally transferred in common mode from the SQUID to the resonator coil, are stopped.

Another problem is the modification of the quality factor of the resonator strongly coupled to the SQUID. This effect is due to the real part of the input impedance of the SQUID [5], and depends both on the bias current and the dc flux of the SQUID sensor. In particular there are working points where the total Q is negative and the resonator is driven into instability. By changing the working point the value of $1/Q$ oscillates approximately between the extreme values $1/Q\approx\pm10^{-4}$. The contribution of the intrinsic dissipation, $1/Q_{int}\approx10^{-6}$, is thus practically negligible and the quality factor is almost completely determined by the SQUID.

In order to avoid the negative Q instabilities due to the SQUID input impedance we implement a damping network. The idea is to reduce the quality factor in order to counterbalance the negative $1/Q$ terms related to the SQUID input impedance.

To realize the damping network we put a capacitor C_d=100 pF between the input coil and the feedback coil, as schematized in Fig. 1(b). The other side of the input coil is grounded, while a resistor R_g is put between the feedback coil and the ground. When the SQUID is operated in flux locked loop mode, a small fraction $R_g w C_d$<<1 of the feedback current flows to ground through the capacitor C_d and the input circuit with a phase shift of 90°, simulating the dynamical effect of a resistor in the input circuit. We put also an additional resistor R_d=0.51 MΩ in series to C_d to avoid high frequency shorting between input and feedback coil.

Following the model in Fig. 1(b) the equivalent change of impedance in series to the resonator due to the damping network can be calculated. The real part of this additional impedance changes the inverse of the quality factor as:

$$D\left(\frac{1}{Q}\right)= bR_g$$

where the constant b depends on the circuital parameters. Thus choosing a suitable value for the room-temperature resistor R_g can counterbalance every negative SQUID contribution to $1/Q$. In our experimental set-up the proportionality constant is $b=3.3\times10^{-7}\ \Omega^{-1}$. By choosing a resistor R_g of 3 kΩ the resonator is stable in all SQUID working points with $1/Q$ of the order of 10^{-3}.

We remark the fact that the resonator is damped by means of a feedback loop and no additional passive dissipation is really introduced in the resonator. The effect is thus a cold damping. The additional apparent resistance does not add noise and the noise sources of the SQUID amplifier are not changed.

4. Noise measurements

A noise model of the SQUID coupled to the high Q resonator is shown in Fig. 1(a). The SQUID is conventionally modeled as an ideal current amplifier with two noise sources: a current noise source I_n in parallel with the input port that provides for the additive noise, and a voltage noise source V_n in series with the input port that acts as a back action generator on the input circuit. The input impedance of the SQUID is represented by a pure inductance L_i. A noise-free resistor r_c is added to the model to take into account the effect of the real part of the SQUID dynamic input impedance and the damping network. A voltage noise source V_{th} is associated to the intrinsic dissipation of the resonator, represented by the resistance $r=w_0L_r/Q_{int}$. Its power spectral density is $4k_BTr$, where T is the resonator temperature.

The SQUID output noise is roughly the superposition of a lorentzian-shaped narrowband noise centered on the resonance frequency ν_0 and a white broadband noise due to the SQUID.

Two voltage noise sources act on the resonator and contribute to the narrowband noise: the SQUID back action noise V_n and the resonator thermal noise V_{th}. It is possible to estimate the back action contribution, and hence S_{vv}, by subtracting the calculated thermal noise from the measured value of the narrowband noise. Technical details on the measurement method are given in a previous article [10]. Narrowband noise measurements were performed at the fixed resonance frequency n_0=1671.4 Hz in the temperature range 1.5 - 4.2 K. The measured values of the back action noise spectral density, expressed in units of energy per unit bandwidth $e_v=S_{vv}/(2w_0^2L_i)$, are plotted in Fig. 2(a). The slope of the linear fit, (65±10) $\hbar$ K^{-1}, is in good agreement with the Clarke-Tesche-Giffard (CTG) theory [11], within the measurement errors and the manufacturer's precision on the SQUID parameters. On the contrary, the intercept of (150±30) $\hbar$ is not predicted by the theory, and could be related to a 1/f noise contribution or to some not identified source of excess noise.

The additive current noise I_n was measured in the more extended temperature range 25 mK – 4.2 K in a separate run in which the input coil of the SQUID was left open, so that the back action voltage noise gives no contribution [7]. The measured spectral density S_{ii} at $w=w_0$, expressed conventionally as energy resolution e, is plotted in Fig. 2(b). e decreases linearly with a slope of 91 $\hbar$ K^{-1}, according to CTG theory, until approximately 300 mK, and levels off to a constant value at lower temperatures. The saturation could be due to the hot electron effect [12]. A non-negligible 1/f contribution explains the intercept of about 60 $\hbar$ in the linear fit.

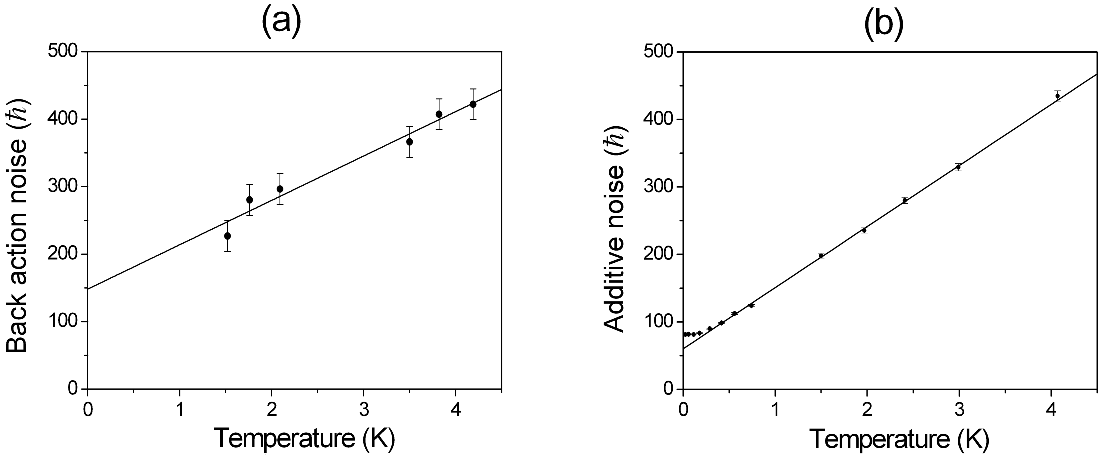

Figure 2. Measured power spectral densities of the SQUID noise sources, expressed in units of energy per unit bandwidth at $w=w_0$, as function of temperature: (a) back action voltage noise $e_v=S_{vv}/(2w_0^2L_i)$ and (b) additive current noise $e=S_{ii}\times(L_i/2)$. Straight lines represent the linear fits of the experimental data.

The fact that the flux to voltage characteristics do not change significantly between the open circuit and the resonator circuit configurations supports the hypothesis that the properties of the SQUID, and hence the noise sources, remain the same in the two measurements. This behaviour is probably related due to some high frequency capacitive shunting of the input coil or to the stray capacitance between the input coil and the SQUID loop that prevent Josephson currents to flow into the input circuit [13]. The most important consequence is that, from these two series of measurements, the approximate noise temperature $T_n=(S_{vv}S_{ii})^{1/2}/(2k_B)$, at the resonance frequency n_0, can be computed. This estimation of T_n is approximate because it neglects the cross-correlation spectral density S_{iv}. However, from the definition (1), it follows immediately that a non zero value of S_{iv} always decreases T_n, so that this procedure gives in any case an upper limit on the true noise temperature.

The minimum value T_n=16 μK, obtained at 1.5 K, is the best measured upper limit on the amplifier noise temperature and corresponds to a minimum detectable energy of 200 $\hbar w$ in an optimally matched resonant GW detector with resonance frequency w. By extrapolation of our data down to 100 mK, a sensitivity of the order of 100 $\hbar w$ is predicted for an optimally matched ultracryogenic GW detector.

Finally it should be pointed out that, when a SQUID is mounted on a real GW detector, excess noise arising from the electromechanical transducer could degrade the effective performance of the SQUID [14]. For this reason the SQUID has been recently mounted on the capacitive transducer that should be used in the next run of AURIGA. A first encouraging partial report on this work has been presented elsewhere in this Conference [15].

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