100 $\hbar$ SQUID AMPLIFIERS FOR THE ULTRACRYOGENIC GRAVITATIONAL WAVE DETECTORS

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One of the important operation parameters for the sensitivity of the cryogenic resonant detectors is the noise temperature of the dc SQUID amplifier used to detect the signal from the displacement transducer. In the limit case of a detector with infinite mechanical quality factor Q, the minimum detectable energy is given by the amplifier noise temperature times the Boltzmann constant. In practice, thanks to resonating low-loss electrical networks which can improve the noise matching between SQUID amplifier and displacement transducer, this limit can be approached also with finite quality factors. For these reasons we study the behavior of systems composed of high Q electrical resonators strongly coupled to low noise SQUID amplifiers. Besides to provide useful indications for the realization of the noise matching electrical networks, these measurements have permitted a full noise characterization of SQUID amplifiers with an energy sensitivity of the order of 100 $\hbar$ at audio frequencies and at 1.5 - 4.2 K.

1 Introduction

The effect of an impinging gravitational wave on the sensing element (a 2 ton, 3 meter length metal bar) of a resonant gravitational wave detector is a small vibration of the ends of the bar. The vibration is converted into an electrical signal by a capacitive or inductive resonant electromechanical transducer. Besides suitable seismic and ambient isolation, the important parameters for the detector sensitivity are a low operation temperature to reduce the thermal vibration noise of the bar, a high mechanical Q of the bar and transducer, and a low noise of the amplifier used to detect the signal from the transducer. In Fig. 1 it is shown the electromechanical scheme of the ultracryogenic AURIGA detector [1] which operates with a resonant capacitive transducer and with a SQUID amplifier. The matching transformer has the function to couple the output impedance of the transducer (a capacitance of a few nF) to the input impedance

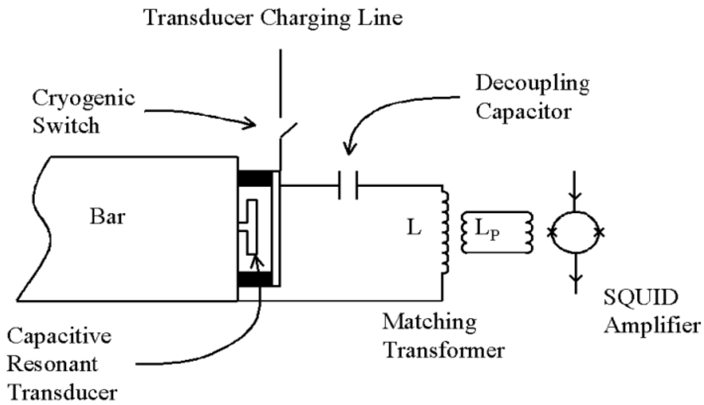

Figure 1: Electromechanical scheme of the AURIGA gravitational wave detector

of the SQUID (a small inductance $L_i \simeq 2\mu H$). The current through the input inductance is converted by means of the coupling M_i in a magnetic flux at the SQUID loop and then in the SQUID output voltage (see Fig. 2 a)). In this paper we consider the role of the SQUID and of the matching network in defining the sensitivity of the detectors with capacitive resonant transducer.

As regards the problems related to the use of a SQUID with a high Q resonant input load (possible instabilities of the system due to a negative real part of the dynamic input impedance of the SQUID), a detailed discussion is reported in Ref. 2.

As for any other amplifier, the noise model of the SQUID amplifier is constituted by an ideal noise free current amplifier with two partially correlated input noise sources: a current noise source in parallel with the input port (additive noise I_n) and a voltage noise source in series with it (back action noise V_n) (see Fig. 2 b)). In many uses of the SQUID the back action noise can be neglected. If this approximation is made in the case of the resonant detector, the detector bandwidth is fully determined by the SQUID additive noise. Consequently, a way to increase the detector sensitivity consists in developing SQUID amplifiers with an additive noise as low as possible.

In section 2 it is described the design used to realize the low noise SQUID which will be employed in the next AURIGA run and the results obtained on bench. The approximation

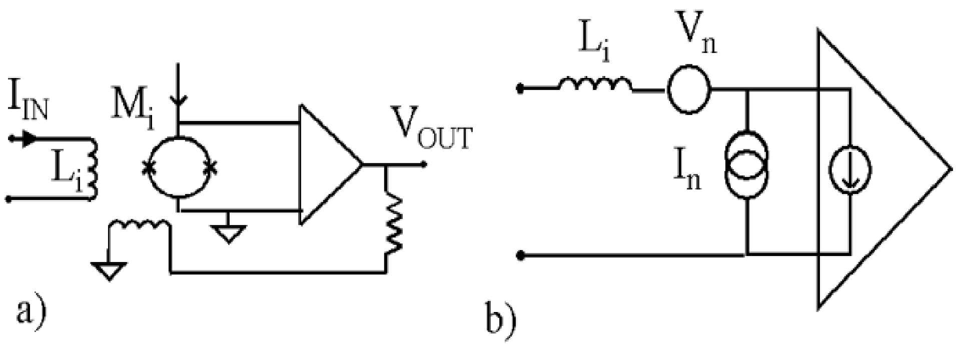

Figure 2: a) Schematic circuit diagram of a flux locked loop SQUID amplifier and b) its noise model.

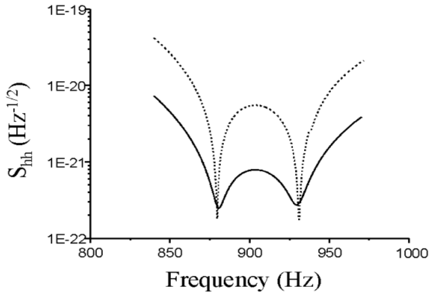

Figure 3: Effect of the tuning of the third electrical mode on the mechanical ones: tuned (solid line), untuned (dashed line)

which considers only the additive noise holds until the back action noise is that expected from the theory [3] (this is not always found in practice), and until the SQUID-bar coupling (transducer efficiency) and the quality factors of the bar and the transducer are not too high. In fact, with very high Q and transducer efficiency the detector sensitivity can approach that of the Giffard's limit, the sensitivity limit which can be achieved with a lossless detector and which is fully and only determined by the noise temperature of the amplifier. In the approximated expression which neglects the correlation term the noise temperature is given by $T_n = \sqrt{S_v S_i}/2k_B$ where S_i and S_v are the noise monolateral spectral densities of I_n and V_n. Then, to obtain a full noise characterization of the SQUID amplifier and evaluate the noise temperature of the SQUID amplifier and, hence, the detector limit sensitivity, it is necessary to measure not only the additive noise S_i but also the back action noise S_v. In section 3 we present a short description of the back action noise measurement technique, which is based on the use of high Q LC resonators strongly coupled to the SQUID, and the obtained results.

Besides the amplifier sensitivity, also the matching network between the bar and amplifier is very important for the detector sensitivity. Price has presented a theory for the optimal design of detectors with multimode network by generalizing the Giffard's limit to a generic instrument consisting of a passive two port network followed by a linear amplifier subject to a signal with an arbitrary spectrum. It is shown that the optimal matching network permits the achievement of the lossless sensitivity limit even if its modes have relatively low quality factors and provides a larger bandwidth than the one mode systems. Price considered only mechanical matching network but substantial advantages can be obtained also with electrical matching network. In fact, besides the two mechanical modes of bar and transducer (see Fig. 1), there is a third electrical mode constituted by the transducer capacitance and by the inductance of the primary coil of the matching transformer. The tuning of the third mode on the mechanical ones is convenient only if its Q is comparable to that of the bar and transducer, that is of the order of 1 million, and if the noise of this mode is totally thermal. In the simulation of Fig. 3 it is shown as an example the effect of the tuning of a high Q electrical mode with thermal noise. The operation parameters of the detector are: bar (and transducer) temperature 100 mK, quality factors of the two mechanical modes 3×10^6, transducer bias field 7×10^6 V/m, SQUID noise temperature 15 μK. The detector sensitivity, expressed in strain noise spectral density S_{hh} $(Hz^{-1/2})$, is shown in two cases: the electrical mode with $Q_{el} = 400000$ tuned on the mechanical ones (solid line) and untuned (dashed line). The effect of the tuning on the detector sensitivity, in particular on the bandwidth, is evident. The indication that comes out from these simulations is to develop LC resonators with quality factors of the order of 1 million and able to operate showing thermal noise, in order to apply this experience to the matching transformer of the resonant detectors.

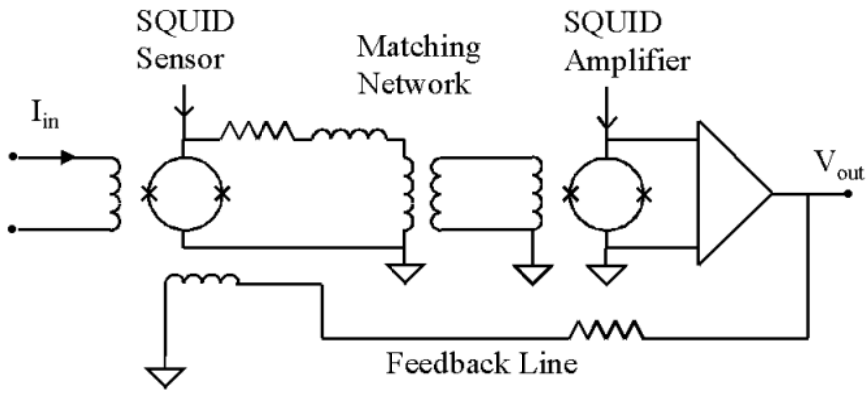

Figure 4: Two-stage SQUID amplifier with flux locked loop

2 The two-stage SQUID amplifier

In Fig. 4 it is shown the two-stage configuration we have used to improve the noise performance of the AURIGA SQUID amplifier[4]. In this configuration the output voltage signal produced by the first SQUID is not sent to a room temperature electronics but amplified by a second SQUID which produces the feedback flux to make linear the response of the system.

This configuration is more complicated than the single-stage one but offers some advantages. First of all, the noise contribution of the room temperature electronics can be made negligible. Second, the effect of the electromagnetic interference picked up by the long cable between the cryogenic components and the room temperature electronics is reduced. Third, as the main part of the noise is produced by the first SQUID, the noise of the two-stage SQUID is thermal, that is it scales with the temperature. This is not true for a single stage SQUID as is shown in Fig. 5 where the temperature behavior of the energy resolution from the additive noise is plotted for two SQUID amplifiers: the same SQUID chip operated single stage and two stage. The noise of the single stage SQUID has an important temperature independent component, which makes useless the cooling at ultracryogenic temperatures. The noise of the two-stage is almost thermal down to 300 mK and then saturates to 35 $\hbar$ probably because of the hot electron effect[5] in the SQUID shunt resistances.

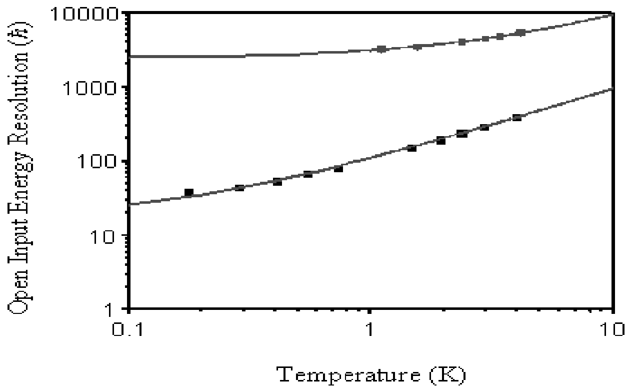

Figure 5: The temperature behavior of the energy resolution from the additive noise for two SQUID amplifiers: the same SQUID chip operated single stage (the data at higher energies) and two stage.

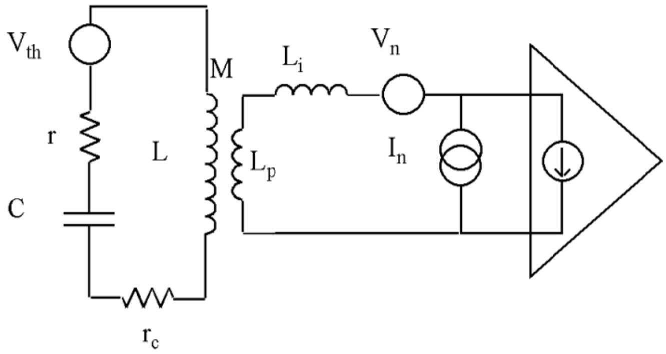

Figure 6: The noise circuit model used in the analysis of the back action noise measurements

3 SQUID noise temperature measurements with high Q LC resonators

To measure the back action noise and achieve a full noise characterization of the two-stage SQUID amplifier we have strongly coupled the SQUID to a high Q LC resonator as indicated in Fig. 6.

The high Q LC resonators are based on low-loss low-stray-capacitance superconducting coils and on commercial teflon capacitors housed in a superconducting case [6]. The typical resonance frequencies $\nu_0 = \omega_0/2\pi$ are in the range 200 Hz - 20 kHz with quality factor of the order of 1 million. The noise model for the resonator-SQUID system considers the thermal noise source V_{th} with spectral density $4k_BTr$ due to the intrinsic losses of the resonator ($Q_i = \omega_0 L_r/r$) and the noise sources V_n and I_n of the SQUID amplifier. A noise-free resistor r_c is included in the model to take into account the effect of the real part of the SQUID dynamic input impedance and is responsible for the apparent quality factor $Q_a = \omega_0 L_r/(r + r_c)$. The noise spectrum at the SQUID output has a Lorentzian peak at the resonator resonance frequency. The expected variance of the noise peak is

$$\sigma^2 = (Q_a/Q_i)A^2\left[\frac{k_BT}{L_r} + Q_i\frac{S_v(\omega)}{4\omega_0}\left(\frac{M}{L_tL_r}\right)^2\right] \tag{1}$$

where the first component is due to the resonator thermal noise and the second one to the SQUID back action noise. $L_t = L_i + L_p$, $L_r = L - M^2/L_t$ is the coil inductance reduced by the coupling to the SQUID, and A is the gain between the resonator current and the SQUID output voltage . If the coupling M between the SQUID and the resonator is strong enough and the Q_i of the resonator is high enough, the back action noise can be emphasized over the thermal noise. Given the back action noise it is easy to calculate the noise temperature of the SQUID amplifier.

As shown in fig 7, we have measured the noise temperature of the two-stage SQUID amplifier as a function of the operation temperature at 1670 Hz and at 11 kHz [7]. The results constitute the lowest noise temperatures ever measured in an amplifier. The intercept of the data at 1670 Hz is different from zero because of a non-thermal 1/f component which is also present in the additive noise. The best noise temperatures are equivalent to an energy resolution $\epsilon = k_BT_n/\omega_0$ of 120 $\hbar$ at 11 kHz and to 200 $\hbar$ at 1670 Hz. The slopes are in agreement with the theory within a factor two. We suspect that this disagreement is not due to some inaccuracy in the values of the SQUID parameters used to calculate the expected noise temperature but to a magnetic noise source near or in the SQUID chip.

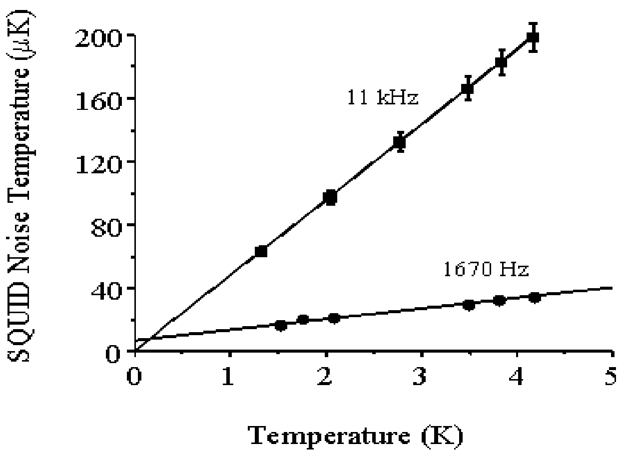

Figure 7: Noise temperatures of the two-stage SQUID amplifier as a function of the operation temperature

4 Conclusions

The experience gained with the tests on high Q LC resonators strongly coupled to low noise SQUIDs has been used in the noise characterization of a two-stage SQUID amplifier and in the realization of the new AURIGA readout. This is constituted by a heavier capacitive transducer with tuned electrical mode read by a two-stage SQUID amplifier.

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