A new capacitive read-out for EXPLORER and NAUTILUS

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Abstract. We describe the present status of a new read-out for the EXPLORER and NAUTILUS gravitational wave detectors. The read-out is based on a double-gap capacitive transducer and a double-SQUID amplifier. The transducer has been tested at liquid helium temperature and a Q of $1.0{\cdot}10^6$ has been measured with a biasing field of 20 MV/m. The double-SQUID amplifier has been tested down to 2 K with a high-Q resonant input load, showing very good stability and energy resolution, of about $70\hbar$. With the new read-out, NAUTILUS, cooled to 100 mK, could reach a peak sensitivity of $3 \cdot 10^{-22}\mathrm{Hz}^{-1/2}$ and a bandwidth, at the level of $10^{-21}\mathrm{Hz}^{-1/2}$, of about 35 Hz.

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1. Introduction

The gravitational wave detectors EXPLORER [1] (at CERN) and NAUTILUS [2] (at INFN Frascati National Laboratories) are both cylindrical bars made of alluminum 5056, with a mass of 2350 kg, length of 3 m and diameter of 0.6 m. Both EXPLORER (in 1999) and NAUTILUS (in 2002) have been equipped with new "rosette" capacitive transducers [3] and new d.c. SQUIDs. These upgrades resulted in a considerable increase of the useful signal bandwidth and, thus, in an increase of sensitivity.

At present EXPLORER is cooled to 2.6 K and NAUTILUS to 3.5 K, both reach peak sensitivities of about $1 \div 2 \cdot 10^{-21}\mathrm{Hz}^{-1/2}$ and a bandwidth, at the level of $10^{-20}\mathrm{Hz}^{-1/2}$, of about 45 Hz for EXPLORER and 35 Hz for NAUTILUS. The duty-cycle is of the order of 90%, only limited by cryogenic operations. These results have been achieved using a read-out system based on capacitive transducers with a gap of the order of 10μm and single stage SQUID amplifiers with energy resolutions of a few thousand $\hbar$s.

2. New read-out

In a resonant detector, the read-out plays a crucial role in determining the overall sensitivity. It can be easily seen that the bandwidth of a single mode detector [1] is given by

$$\Delta f = \frac{f_0}{Q\sqrt{\Gamma}} \tag{1}$$

where Γ is a dimensionless ratio of wideband (amplifier wideband noise ϵ_{ii}) to resonant (thermal of the detector and back action of the amplifier ϵ_{vv}) noise. Moreover, it can be seen that, using the simplest analysis [4], the minimun detectable energy ΔE_{min} is given by

$$\Delta E_{min} = k_B T_{eff} \approx \frac{k_B T}{\beta Q} + 2k_B T_n \tag{2}$$

here T_{eff} is the pulse detection effective temperature of the detector, k_B is the Boltzman constant, T the thermodynamical temperature of the detector, Q its quality factor and $T_n = \sqrt{\epsilon_{vv}\epsilon_{ii}}\omega_0/(2k_B)$ is the noise temperature of the amplifier. Thus the importance of obtaining high values for β and Q and, on the other hand, as small as possible values for T_n.

2.1. Double-gap Capacitive Transducer

Figure 1. A picture of the double-gap transducer. It is possible to see the two electrodes and the resonator.

The working principle of all transducers is to store electromagnetic energy in a volume, usually a narrow gap, one of the walls of which is part of the antenna. The motion of this wall, arising from vibrations in the antenna, induces a modulation of this energy which is detected and amplified as an electrical signal.

The transduction efficiency β is given by the ratio between the mechanical energy of the transducer and the electromagnetic energy stored in the gap, and for a capacitive transducer becomes

$$\beta = \frac{CE^2}{m\omega_0^2} \tag{3}$$

where C is the total capacitance of the transducer, E the biasing field, m the resonator equivalent mass and ω_0 its resonance frequency. It turns out from eq. (3), that a way to increase β is to increase the capacitance C. The idea followed by the ROG Collaboration is the double-gap trasducer (fig. (2) shows a scheme of the device). A "rosette" resonator is enclosed between two identically spaced electrodes, i.e. two identical gaps. The circuit diagram of the transducer, the matching transformer and d.c. SQUID amplifier is showed in fig. (3). This setup has the net effect to double the total capacitance C of the transducer, thus to increase the transduction efficiency β.

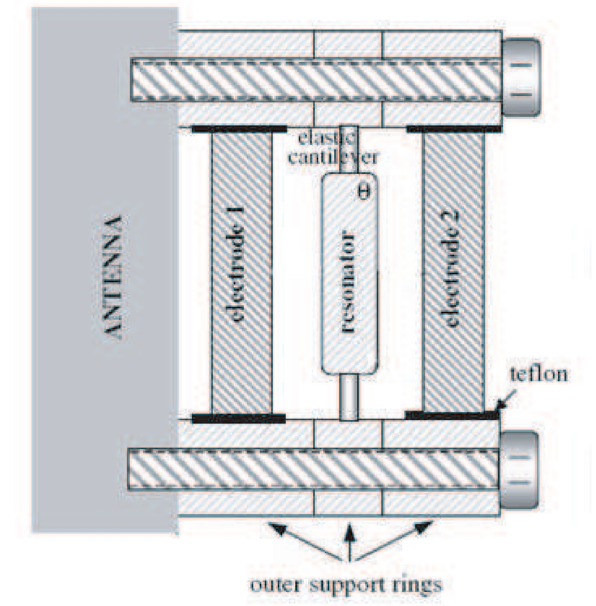

Figure 2. A schematic view of the double-gap transducer.

Moreover, by properly biasing the two gaps, one with a positive voltage and the other with a negative voltage with respect to the resonator, it is straightforward to see that the current flowing in the primary coil of the transformer is twice that in the case of a single gap transducer.

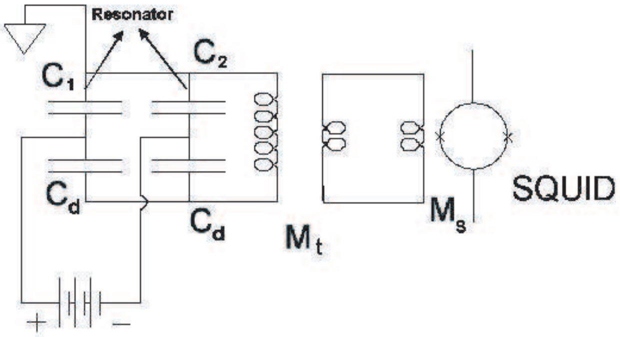

Figure 3. The circuital scheme of the double-gap transducer, connected to the matching transformer and d.c. SQUID amplifier.

A double-gap transducer has already been designed, assembled and tested at liquid helium temperatures. The value for both gaps was of the order of 15μm and the mechanical quality factor was found to be $1.0 \cdot 10^6$ when the transducer was biased with a field of about 20 MV/m. Moreover the dependence of ω_0 on E_{bias} has been fully investigated finding a good agreement between the measured and calculated [5] values.

2.2. Double SQUID

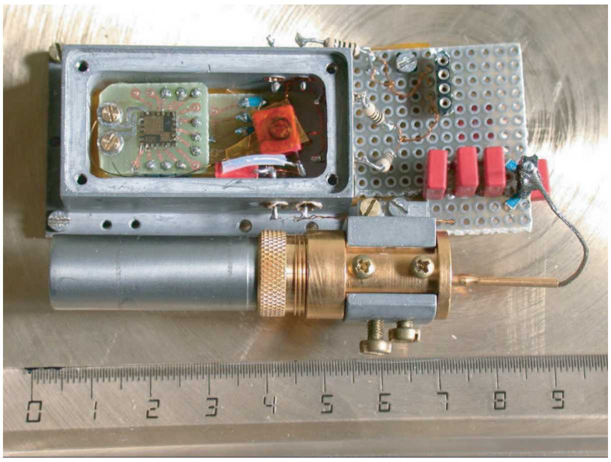

Figure 4. A picture of the ROG double SQUID amplifier. In the upper left part of the figure it is possible to see the sensor SQUID.

In most practical applications the sensitivity of a SQUID with a standard modulation read-out is usually good enough. However gravitational wave detectors require the highest possible sensitivity of a d.c. SQUID. In this case the standard read-out may not be the best solution, because the overall sensitivity can be limited by the room-temperature preamplifier noise. With this setup an energy resolution of about $3000\hbar$ has been measured [6] .

In the last years, it has been shown [7, 8, 9] that a double-SQUID system can reach quantum limit energy resolution and that a double-SQUID system can be arranged in a stable configuration when connected to a high-Q resonant circuit [10].

The double-SQUID amplifier of the ROG Collaboration (shown in fig. (4)) is made of a sensor d.c. SQUID, developed by the Institute of Photonic and Nanotechnologies of CNR, while the preamplifier SQUID is a commercial Quantum Design d.c. SQUID. The performances of the device are very good: with open input and open loop it exhibited [7] energy resolutions equal to $28\hbar$ at 4.2 K and $5.5\hbar$ at 0.9 K.

To avoid the instabilities that arise in d.c. SQUID devices connected to high-Q resonant input loads, it has been necessary to install a cold damping network [11]. The system has been successfully tested with a high-Q[1] electrical resonator in the temperature range 2 K-4.2 K. The device showed very good stability. The broad band energy resolution has been measured by acquiring the output spectra of the double-SQUID amplifier, coupled to the high-Q input load. Then the spectra have been averaged over a few hundred hertz around the resonance frequency of the LC resonator. The broad band energy resolution is calculated from $\epsilon_{ii} = L_i S_{in}/2$, where L_i is the input inductance of the sensor SQUID and S_{in} is the noise spectral density at the input of the SQUID. The best energy resolution is about $(70 \pm 8)\hbar$ at 2 K. The parameters of the high-Q resonant input load do not allow a direct measurement of the back action noise spectral

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[1] The parameters of the circuit are L_0=96 mH, $Q_0=0.7 \cdot 10^6$, k=0.38 and f_0= 1740 Hz

density. Further testing at lower temperatures and with higher Q and k resonant input load, to measure back action noise, is planned.

3. Conclusions

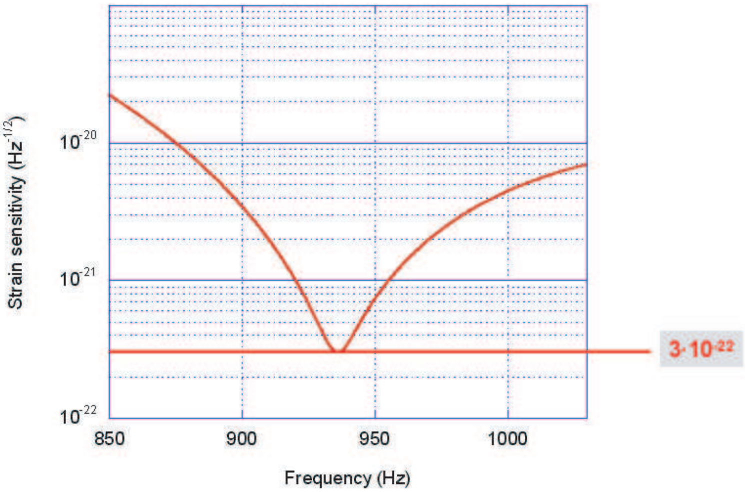

Figure 5. Expected sensitivity curves for NAUTILUS cooled to 100 mK and equipped with the new read-out.

Both the double-gap transducer and the double-SQUID amplifier have been succesfully tested in separate runs. By the end of the year the complete read-out chain will be assembled and tested at low temperatures.

It is possible to calculate [12] the sensitivity (shown in fig. (5)) that can be achieved by NAUTILUS, cooled to 100 mK, with the new read-out. In the calculation of the detector sensitivity, a conservative value of $\epsilon_{ii} = 50\hbar$ for the SQUID energy resolution has been used, since saturation effects could raise, as observed on similar systems at temperatures below 200 mK [13]. The peak sensitivity is around $3 \cdot 10^{-22}\text{Hz}^{-1/2}$ and the bandwidth, at the level of $10^{-21}\text{Hz}^{-1/2}$, is about 35 Hz. The noise temperature of the detector should be around 7μK corresponding to a sensitivity to 1ms bursts $h = 2.1 \cdot 10^{-20}$.

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