NEARLY QUANTUM-LIMITED SQUIDS FOR A GRAVITATIONAL WAVE ANTENNA

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0. Abstract

Nearly quantum-limited Superconducting QUantum Interference Devices (SQUIDs) have to be used in resonant mass gravitational wave antennas to reach a displacement sensitivity of the order of 10^{-21} m/√Hz in a bandwidth of 100 Hz around the resonance frequency of about 900 Hz. The design of these SQUIDs will be described. We show that a good coupling between the inductive readout circuit and the SQUID can be obtained by choosing a relatively large hole size of the washer-type SQUID configuration.

Keywords: SQUIDs, quantum limit, gravitational wave antenna

1. Introduction

In the Netherlands an initiative has been taken to build a resonant mass gravitational wave antenna under the project name GRAIL. Groups from the Universities of Leiden, Amsterdam, Eindhoven and Twente and the high-energy physics center NIKHEF (Amsterdam) constitute the GRAIL team. The Twente group will be responsible for the readout system that has to detect the very small displacement of the spherical mass antenna after the passage of a gravitational wave.
The antenna will have a diameter of 3 meters and a mass of about 110 tons. The operation temperature of 10 mK will be reached with a powerful dilution refrigerator of 100 μW cooling power at that temperature. The vibration damping of the support system of the sphere will be 320 dB. A gravitational wave will give an extremely small quadrupole distortion of the antenna dimensions. In order to be able to detect gravitational waves, the displacement sensitivity of a readout device should be of the order of 10^{-21} m/√Hz in a bandwidth of 100 Hz around the resonance frequency (900 Hz) of the sphere. This sensitivity is a factor of 100 better than that of existing antennas [1]. It is expected that with this extreme sensitive system, gravitational waves can be detected for the first time in history.

In this paper we will describe the motion sensor we aim for in the GRAIL design. For reaching the extreme displacement sensitivity superconducting sensors that operate near the quantum limit are necessary.

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2. The overall system

A schematic picture of the readout system for the displacements of the spherical antenna is given in figure 1. The system consists of a mechanical transducer, a superconducting inductive network and a superconducting sensor (SQUID). The mechanical transducer consists of two masses with a resonance frequency very close to that of the sphere. When the vibrational energy is transferred to the last mass an amplitude gain of more than 100 can be obtained. The last mass is superconducting and its displacement modulates the self inductance of the coil facing this mass. The superconducting inductive circuit carries a persistent current and the modulation of the coil inductance induces a small ac current in the loop due to the principle of flux conservation. The ac current is sensed by the most sensitive sensor for magnetic flux that exists, being the SQUID. In total six sensors will be placed on the sphere in order to be able to determine the polarization and direction of the gravitational wave.

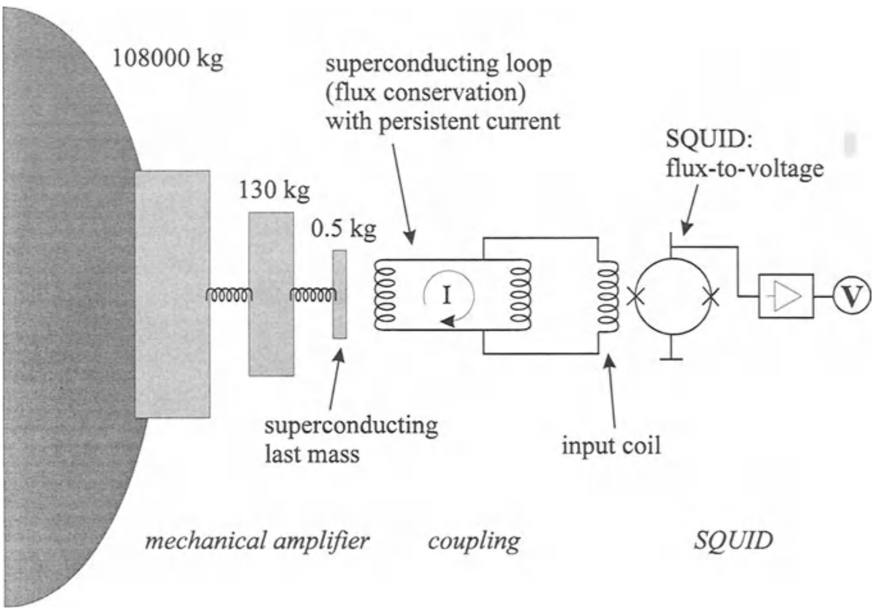

Fig. 1 - A schematic picture of the displacement readout system of the gravitational wave antenna.

The basic scheme of a dc SQUID is depicted in figure 2a. The two Josephson junctions, with a critical current I_0 and a self-capacitance C, are connected in parallel by a superconducting loop with inductance L_{sq}. To eliminate hysteresis on the current *vs.* voltage characteristic each junction is shunted by an external resistor R_s.

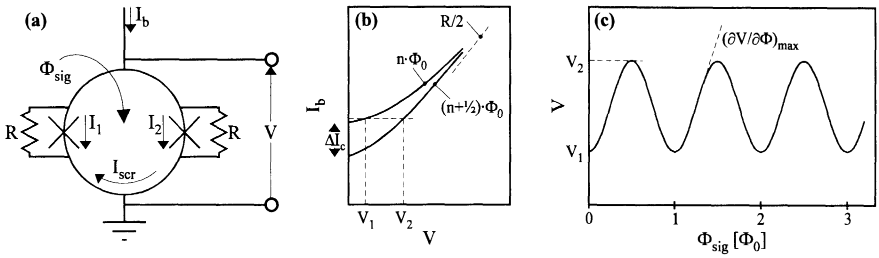

Fig. 2 - Scheme (a), I-V (b) and V-Φ (c) characteristics of a dc SQUID.

When the dc SQUID is biased with a constant current I_b, the voltage V across the SQUID is a function of the signal flux applied through the input coil. If the magnetic flux Φ_{sig} is varied , the voltage V oscillates with a period Φ_0 (one flux quantum) between the values V_1 and V_2, as shown in figures 2b and 2c, while the I-V characteristic oscillates between the two extreme values represented in figure 2b. Thus it is possible to measure the change in the voltage across the SQUID induced by a small change in the magnetic flux threading the SQUID loop. The SQUID plays then as a flux-to-voltage transducer with a transfer function $V_\Phi=(\partial V/\partial\Phi)_I$, which attains its maximum value at a flux around $(2n+1)\Phi_0/4$, n being an integer. However, in most applications the non-linear V-Φ_{sig} characteristic needs to be linearized. The dc SQUID is then operated as a null detector in a feedback loop (the so called "Flux Locked Loop") that provides a linear response. The dc SQUIDs made in the LTD of Twente are washer-type ones fabricated in thin film technology.

The main source of white noise in resistively shunted dc SQUIDS is the Johnson noise in the two resistive shunts R_s. The flux noise spectral density S_Φ, which determines the smallest detectable change in magnetic flux is found to be [2]:

$$S_\Phi = \frac{S_V}{(\partial V/\partial\Phi)^2} \approx 9\cdot\frac{2k_B T L_{sq}^2}{R},$$

where T is the operating temperature of the SQUID, and R is the parallel of the shunt R_s and the intrinsic resistance of the junction R_n.

The energy resolution ε is a convenient parameter to compare the sensitivity of SQUIDS with different inductances:

$$\varepsilon / 1\,\mathrm{Hz} = \frac{9k_B T L_{sq}}{R}.$$

For standard dc SQUIDs, ε is of the order of $10^4\hbar$. For many SQUID applications [3] this value is adequate. However, in order to reach the required sensitivity for a gravitational antenna, SQUIDs with an energy resolution below 10 $\hbar$ are needed.

3. Nearly quantum-limited SQUIDs

In order to design nearly quantum-limited devices suitable for the gravitational antenna, it is necessary to put the former expression of the energy resolution in terms of externally variable parameters of the dc SQUID. The inductance of the SQUID L_{sq} is considered to be mainly that of the washer, and the contribution of the slit is in first approach neglected: $L_{sq} \approx L_w = 1.25\mu_0 D$, where D is the dimension of the SQUID hole in the washer. The intrinsic resistance of the junction R_n is approximately $R_n \approx \frac{\pi}{4}\frac{2\Delta/e}{I_0}$, where $2\Delta/e$ is the gap voltage (~2.8 mV for a Nb based junction) and I_0 is the critical current through it. The capacitance per unit area of junction is supposed to be constant $C/A \approx 0.03$ pF/μm^2. Also the critical current density must be kept constant $J_0 = I_0/d^2 \approx 40 A/cm^2$ (d being the junction size), as all the SQUIDs must be fabricated on the same wafer. Some extra requirements must be fulfilled in the design. First, to minimize the energetic noise the screening parameter $\beta_L = 2L_{sq}I_0/\Phi_0$ should be $\beta_L = 1$. In addition, to ensure the non-hysteretic behavior of the SQUID, the Mc Cumber parameter $\beta_c = 2\pi I_0 R^2 C/\Phi_0$ should be $\beta_c \leq 1$. Finally, the noise parameter, relating the Josephson coupling energy and the thermal fluctuations, should be: $\Lambda = I_0\Phi_0/2\pi k_B T > 10$ for the safe operation of the SQUID.

Taking into account these relations it is possible to write the energy resolution as a function of the temperature T, d and D:

$$\varepsilon/\hbar = 0.453\ T(K) d(\mu m) D(\mu m)^{1/2},$$

T and D fulfilling the operational condition:

$$\Lambda = 0.016 \times 10^6\ T(K)^{-1} D(\mu m)^{-1} > 10.$$

The energy resolution for a fixed temperature of 4.2K is represented in figure 3.

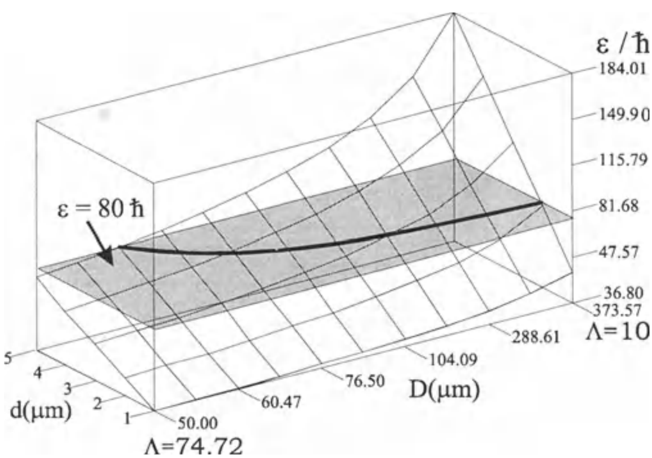

Fig. 3 - The theoretical energy resolution ε of a washer-type dc SQUID as a function of the junction size d and the washer hole D for $J_0 \approx 40$ A/cm², $\beta_C = 1$ and T = 4.2 K.

The above condition at this temperature implies that the SQUID hole size should be: D<374μm. Although in principle there is no lower limit for D, the smaller the SQUID hole size, the larger the number of turns necessary to couple the SQUID, Many problems will then arise. As the theoretical energy resolution is linear with T, to have nearly quantum limited SQUIDs with $\varepsilon \approx 2\hbar$ at 0.1K it is enough that their energy resolution at 4.2K is $\varepsilon \approx 80\hbar$. The intersection of the $\varepsilon \approx 80\hbar$ constant plane with the energy resolution surface defines a line on which a series of SQUIDS, (d,D) characterized, can be chosen. We conclude that SQUIDs with a relatively large hole size can be prepared that reach the quantum-limit at 0.1K. The large hole facilitates the coupling to the SQUID. It is found that junctions with (sub)micron dimensions are then needed. The construction of a number of such devices is at present under process.

4. System aspects

We have calculated the equivalent displacement noise X_{noise}(m/Hz$^{1/2}$) for the GRAIL antenna, according to reference [4]. The results for a 3-mode transducer, i.e. a mechanical transducer consisting of two masses (m_2, m_3) in addition to the antenna mass (m_1) are presented in figure 4. The effective antenna mass is $3x10^4$ kg. The other two masses were varied in calculations, obeying $m_3=m_2^2/m_1$. The mechanical Q-factors were taken as $5x10^6$. The resonance frequency is 900 Hz and T=0.1K. The coil of the inductive circuit with inductance L_t=5μH is a pancake coil and the distance to the facing superconducting mass m_3 is 25 μm. A persistent current of 10 A flows in the circuit. The electrical quality factor of the circuit equals $5x10^6$. The input coil on top of the SQUID has an inductance L_i=2μH. The SQUID used in the calculations is one of the previously designed, with $\varepsilon=80\hbar$ at 4.2K, giving $2\hbar$ at 0.1K. It is found that X_{noise} depends on the value of m_3. In all cases the bandwidth is considerably larger than 100 Hz around the resonant frequency of 900 Hz at a level of 10^{-21} m/√Hz.

In order to obtain L_i=2μH, a large number of turns of the input coil is necessary. In general this will lead to unwanted resonances that disturb the proper operation of the SQUID. It is therefore worthwhile to consider an input coil with less turns leading to a smaller value of L_i. However, then an impedance mismatch between L_t an L_i appears. We have varied L_i in our calculations down to 50 nH. The desired

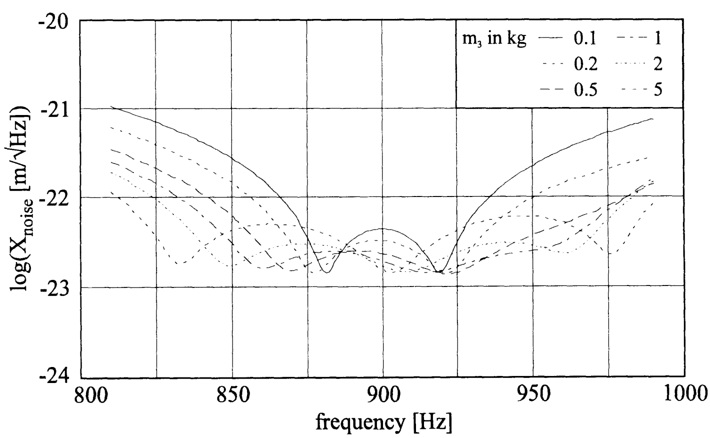

Fig. 4 - Displacement noise spectra for six different values of m_3. Other parameters: L_i = 2 μH, $\varepsilon = 2\ \hbar$, T = 0.1 K.

displacement sensitivity of 10^{-21} m/√Hz is still reached in a very reasonable bandwidth of 80 Hz.

Due to the high mechanical and electrical quality factors, back action effects of the flux locked loop operation can deteriorate the spectral displacement noise features of the system [5]. The feedback current induces not only a flux in the SQUID hole but also in the input coil circuit via the SQUID. In order to avoid this unwanted coupling we propose to mix the internal feedback with an external feedback to the input circuit so that the back action signal via the SQUID is just canceled by the external feedback signal. Also a large bandwidth of the SQUID read out system will contribute to the suppression of the back action effects.

5. Conclusions

We have shown that nearly quantum-limited dc SQUIDs can be obtained with a relatively large hole size in the SQUID washer enabling a good coupling to an inductive circuit that is used for the read out of the small displacements of a resonant mass gravitational wave antenna. With these SQUIDs, a sensitivity level of 10^{-21} m/√Hz can be reached in a bandwidth of over 100 Hz around the central resonant frequency of 900 Hz.

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