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Development of a transducer for MiniGrail

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Abstract
We are developing a two-mode inductive resonant transducer for MiniGrail. We report several quality factor measurements, down to 4.2 K, performed on a scaled size resonator in different conditions: when suspended from a wire and when clamped, by thermal contraction techniques, into a hole of a sphere of 150 mm diameter and 14 kg mass. Q-factor measurements of a first resonator prototype at 4.2 K for MiniGrail are also presented. Finally, a fabrication process for a Nb film pick-up coil is described.

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1. Introduction

We are developing a two-mode inductive transducer for MiniGrail, a 1.2 ton, 65 cm in diameter spherical gravitational wave antenna [1]. A two-mode transducer would provide a larger bandwidth and better electromagnetic coupling in comparison with the single-mode transducer. The advantages of multi-mode transducers have been extensively discussed in the past and prototypes are under development by several groups [2–4].

In this paper we will describe the main features of our two-mode transducer and present the results of some very preliminary tests.

We have investigated the effects on the mechanical quality factor when mounting a CuAl6% resonator on a small size CuAl6% sphere. We have designed a two-mode resonator and performed some preliminary quality factor measurements of the first fabricated prototype. Further, a fabrication process for a Nb film pick-up coil for the inductive read-out has been found that allows for strong films and superconducting connections to resist thermal cycles well, but attempts to run a persistent current in the coil have not been successful yet. In the final section of this paper the expected MiniGrail sensitivity will be discussed in the case of the two-mode transducer mounted on the sphere and inductively coupled to a low noise dc-SQUID.

[1] Web: www.minigrail.nl

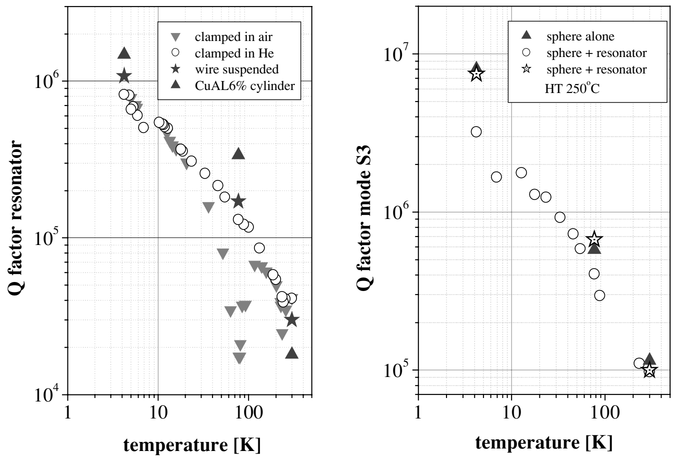

Figure 1. Effect on the quality factor when a resonator is mounted on a sphere.

2. Clamping of a resonator into a sphere of 150 mm diameter and 14 kg mass

An important issue in developing multi-mode mechanical resonators for a GW resonant detector is to find a reliable technique to assemble together different parts of different materials without spoiling the overall mechanical quality factor. Coupling two resonators by the thermal contraction technique has been shown to be rather satisfactory [5], but an extensive study is still lacking. To evaluate how clamping together a resonator and a sphere affects the Q factor of both, we press-fit a small size CuAl6% resonator into a 15 mm deep, 45 mm diameter, conic hole of a 150 mm CuAl6% sphere. The sphere and the suspension system are the same as described elsewhere [6]. The resonator consists of a rosette design [7] spring–mass system. It has a central oscillating mass of about 30 g. The springs are 5 mm thick and are attached to an external body about ten times more massive than the central mass. The resonator is designed in such a way that the contact with the lateral surface of the hole was along a 1 mm thick central ring. The resonant frequency of the 'drum' mode is 14.9 kHz at 4.2 K. The mode is not tuned with any of the spheroidal modes. We first machined the resonator without springs, then annealed it at 750 °C in vacuum for 8 h and finally cut the springs using electro-discharge machining (EDM).

The mechanical Q-factor down to 4.2 K of the sphere–resonator system was measured by observing the decay of the excitation with piezos glued to the resonator and sphere surfaces. The results are shown in figure 1. The first plot shows the quality factor as a function of temperature of the resonator 'drum' mode. Stars show the quality factor when the resonator is suspended from a 100 μm tungsten wire to a brass plate. The Q measured at 4.2 K was 1.1×10^6, close to the value measured with a cylinder machined from the same ingot used for the resonator and heat treated in the same way. Down triangles and empty circles show the Q-factor of the resonator when clamped into the sphere. In the first case, the clamping was obtained by dipping the resonator into liquid nitrogen and then fitting it in air into the sphere hole. Some absorption peaks around 250 K and 77 K have been observed. They are probably due to water and nitrogen molecules condensed between the clamped surfaces. The peaks disappear when clamping is performed in He atmosphere as one can see from the empty circles data. No differences in Q-factor have been observed at 4.2 K. The measured Q-factor was 0.8×10^6. Due to clamping, the quality factor of the resonator 'drum' mode decreased

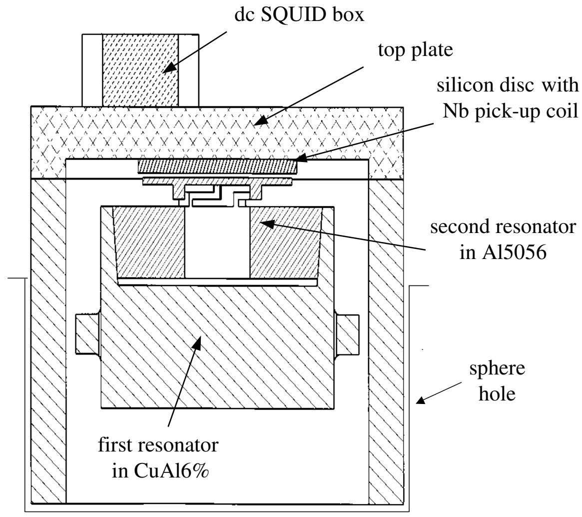

Figure 2. Cross section view of the two-mode transducer.

by about 20%. The effect of clamping on the spheroidal modes is stronger and can be seen in the second graph of figure 1. The *Q* of the third spheroidal mode at 13.8 kHz and 4.2 K is shown. A decrease of about 40% for all the spheroidal and toroidal modes has been observed. After a heat treatment of the sphere with attached resonator at 250 °C in air for 12 h, the high *Q* of the sphere modes was restored. Some spheroidal modes reached a *Q* value higher than 10 million. The *Q* of the resonator decreased after heat treatment, probably due to the strong oxidation of the springs. Etching the resonator while inside the sphere should restore the high *Q*.

3. Design and mechanical *Q*-factor measurements of a first two-mode resonator prototype

In figure 2 we show a schematic view of a first prototype of a two-mode transducer for MiniGrail. Two mechanical resonators are coupled to each other with the second small resonator press-fit into the central mass of the first larger resonator. The top plate holds the superconducting pick-up circuit and the dc-Squid.

The first resonator is made of CuAl6% (the same material as the sphere) and has a central mass of about 450 g and springs cut with a rosette design [7]. The thickness of the springs is 5 mm and the 'drum' mode has a resonant frequency of about 4.3 kHz at 4.2 K. It was fabricated using conventional machining and heat treated at 800 °C for 8 h in vacuum before cutting the springs with EDM. A final stress-relief thermal treatment was performed at 500 °C in vacuum for 4 h.

The second small resonator was made in Al5056. It consists of a 1 mm thick disc 33 mm in diameter supported by four flexure arms. The disc mass is about 2 g. The resonant frequency of the 'drum' mode is 2.5 kHz at 4.2 K. We were not interested, for the measurements shown here, in tuning the two resonators. A similar design has been shown by Geng [8] to give a high quality factor at low temperature. We machined the arms using EDM and conventional machining for the rest of the body. No heat treatment was done for the measurements shown here. In the future, we plan to deposit a Nb film on the disc top-surface for the inductive read-out.

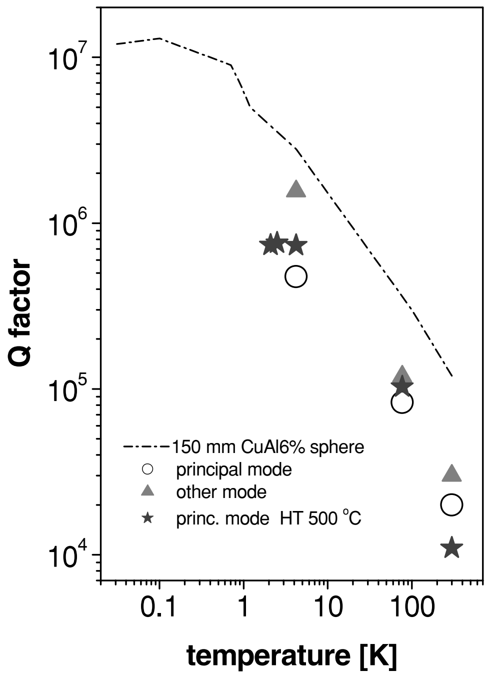

Figure 3. Quality factor of a CuAl6% 'rosette' resonator compared with that of a 150 mm CuAl6% sphere.

In the final design, the mass ratio between the resonators will be chosen to optimize the sensitivity of the detector, and both the resonators will be tuned to one of the spheroidal modes of the sphere.

The graph in figure 3 shows the results of preliminary mechanical Q-factor measurements on our first 'rosette' resonator suspended with a tungsten wire to a brass plate. The resonator 'drum' mode had a quality factor of 0.5×10^6 at 4.2 K that increased to 0.7×10^6 after a stress-relief heat-treatment at 500 °C in vacuum for 4 h. We suspect that the Q-factor is limited by the coupling of the resonator modes with the brass plate. In fact, when we cooled the temperature down to 2 K, by pumping on the bath, the Q did not increase as expected. A vibration damping system is currently in fabrication.

We also performed a measurement of the quality factor of the two resonators assembled together, using the thermal contraction technique described above. To prevent the clamping becoming loose due to the higher thermal contraction of Al with respect to CuAl, the diameter of the Al5056 resonator conic base (figure 2) has been machined bigger than the conic hole diameter in the CuAl6% mass by an amount equal to about three times the contraction difference. The 'drum' modes of the two resonators are not tuned. The quality factors of the 'drum' modes of the two resonators were, respectively, 0.1×10^6 and 0.15×10^6 at 4.2 K. The low Q is probably due to the fact that the Al resonator had not been heat treated during and after the machining process.

4. The superconducting pick-up coil

We will detect the displacement of the second resonator in an inductive way. A superconducting Nb flat coil is placed, at 20 μm distance, in front of the superconducting disc of the second

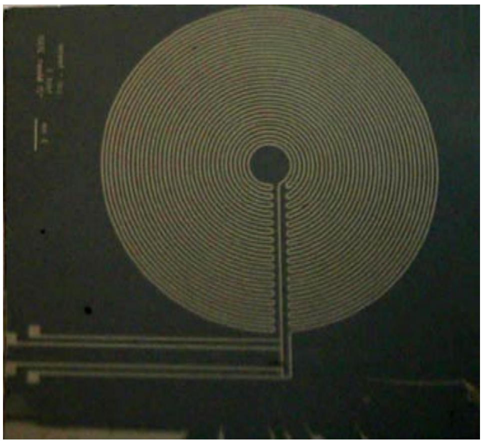

Figure 4. Picture of a pick-up coil obtained from Nb film.

resonator and generates a magnetic field. A second coil picks up magnetic flux changes due to the disc displacement and transfers them to a low noise dc-SQUID. The coil generating the field should carry current as high as 6–7 A in a persistent mode. This technique has been used and developed by the Allegro group for many years [3, 4]. An interesting idea, first explored by Stevenson [9], is to fabricate the superconducting circuit using Nb film deposition and photolithographic processes. It has many advantages, such as high reproducibility, ease in changing the coil geometry and good 2D structure for the pick-up coil, which is crucial to make transducers with micrometre gaps.

We used a simple fabrication process to pattern a Nb film on a silicon substrate. A picture of one of the Nb coils is shown in figure 4. The coil is made out of a 400 nm Nb film. The film is obtained by deposition in an ultra-high vacuum sputtering chamber. The base pressure was around 8×10^{-8} mbar.

The coil has 34 turns 200 μm wide. The space between the turns is also 200 μm. The overall diameter is 33 mm. The calculated inductance of the coil is 330 nH. The coil pattern also includes the pads and the connections to inject persistent current and for the superconducting heat switch.

After depositing the film, the coil was patterned using standard photolithographic techniques. Once the pattern was obtained with a positive photoresist, the residual Nb was etched away by means of an ion beam. The entire process is very easy and can be completed within a week with a totally new coil design. The resistor for the heat switch, an Al strip with a resistance of 4.5 Ω at 4.2 K and about 50 μm apart from the superconducting Nb line to switch to normal, was deposited in a second step.

We measured $T_c = 7.5$ K of the deposited Nb film that increases to 8.5 K by heating up the substrate to 400 °C during the deposition. A crucial point is to find a reliable technique to make high critical-current superconducting connections between the Nb film and the superconducting wires that bring the current. Using some indium and Woods solder in a similar way as described in [10], we were able to obtain mechanically strong connections, highly resistant to thermal cycles, but with a critical current of only 2 A. New tests are in progress to improve this value. Attempts to run persistent current in the coil have not yet been successful.

In the final transducer, the pick-up coil will be coupled, through a superconducting transformer, to a low noise double stage dc-SQUID, under development by the Low Temperature Division Group in Twente [11].

5. Conclusion

We are developing a two-mode inductive transducer for the spherical gravitational antenna MiniGrail. An overview of the design and the progress in fabrication of the mechanical and electrical parts of the transducer has been presented.

The burst strain sensitivity that MiniGrail should reach with the transducer under development, assuming a Q of six million at the working temperature of 20 mK and a dc-SQUID sensitivity of 200 $\hbar$, is 4×10^{-20} at 3.2 kHz, with a bandwidth of about 200 Hz.

Acknowledgments

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