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Tests with superconducting re-entrant cavities for transducer applications in gravitational wave detectors

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Abstract
We studied the niobium re-entrant cavity utilized by the Australian group in the Niobe gravitational wave detector. Instead of using their non-contact re-entrant cavity, we plan to change it to a closed one to be used in the parametric transducers of the Brazilian Mario Schenberg detector. The performance of the transducer depends on some cavity parameters such as the electrical Q and the electrical coupling. We measured the resonant frequency and the loaded electrical Q as a function of the probe position in a closed niobium $\sim$15 GHz cavity operating at 4.2 K.

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1. Introduction

Parametric transducers used in gravitational wave detectors convert mechanical vibrations into electrical signals at much higher frequency, amplifying the signal energy by the intrinsic parametric gain. A kind of parametric transducer, which will be used in the Brazilian Mario Schenberg detector [1], was developed by both the Japanese and the Australian groups [2, 3]. This transducer consists of a re-entrant superconducting niobium cavity (figure 1) having a central post with a narrow gap between its top and an oscillating end wall, mechanically coupled to the gravitational wave antenna at its resonant frequency.

In our study, we reproduced the cavity used by the Australian group in Niobe. Figure 2(*a*) shows the cavity we use in our experiment. The cavity is 8 mm in diameter and 1.4 mm high.

The re-entrant cavity is basically an LCR resonator, where the capacitance is determined by the gap between the central post and the end wall, and the inductance is mainly due to the magnetic field circulating around the central post of the cavity. The capacitance of the cavity is modulated by the motion of the end wall [4].

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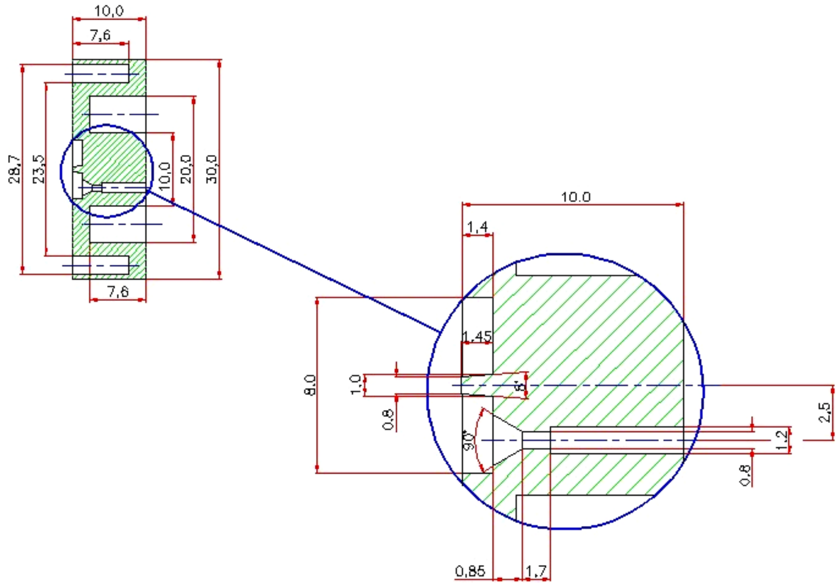
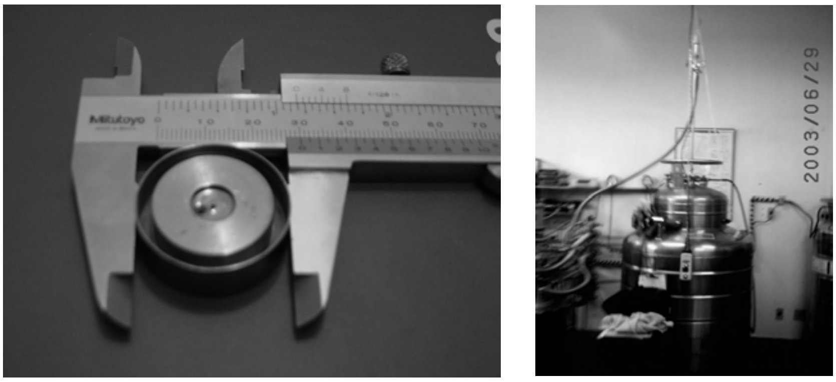


Figure 1. Schematic view of the microwave cavity.
(This figure is in colour only in the electronic version)



(*a*) (*b*)

Figure 2. (*a*) The re-entrant cavity; (*b*) view of the rod cryostat, which contains a pillbox attached at its end, inserted into the helium tank.

2. The experimental setup

Our objective in this experiment is to measure the loaded electrical Q and the resonant frequency for the niobium superconducting cavity as a function of the probe position.

In order to change the electrical coupling during the experiment we have constructed a small pillbox Dewar joined to a long stainless steel tube, inside which there is an inner tube that can be rotated. We are able to adjust the position of the probe inside the cavity with reasonable precision by turning the inside tube relative to the outside one. The probe, which is rigidly connected to the inner rotating tube, is the central conductor of a UT-47 coaxial cable.

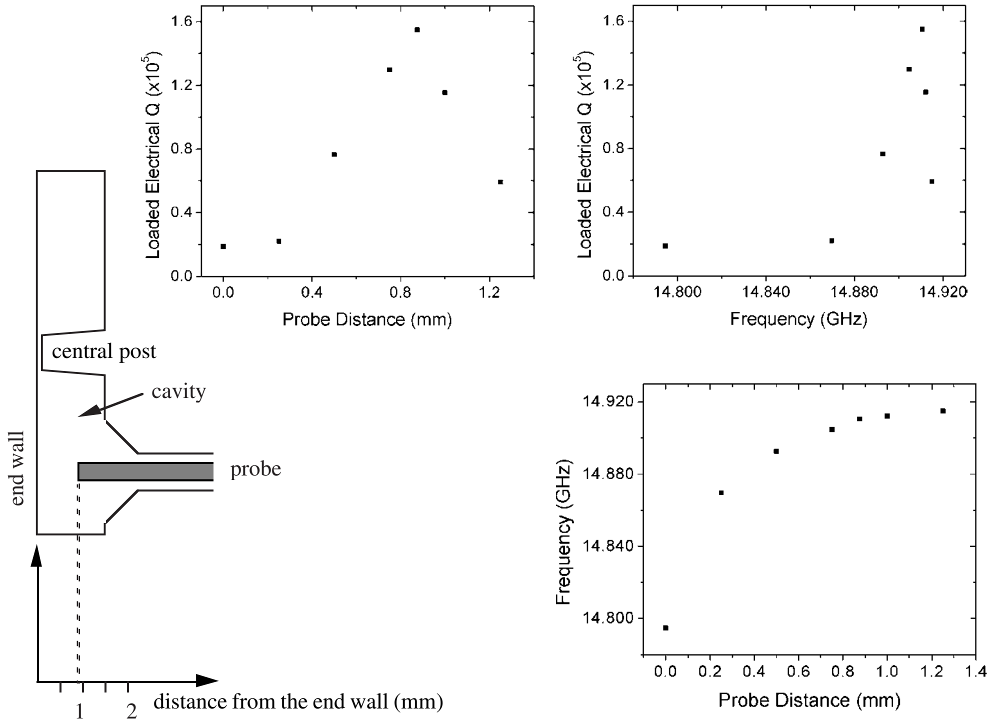


Figure 3. Experimental results.

In order to achieve a very high Q all the measurements have been done at 4.2 K, making use of the superconductivity properties of the niobium, which becomes a superconductor below ~9 K.

We did the cool down by plugging the rod into the helium tank. The cavity was inside a pillbox attached at the bottom end of the rod cryostat (figure 2(*b*)). The vacuum and electrical connections were all at the top end of the rod.

3. Electrical *Q*s and coupling

A resonant cavity is characterized by two parameters, its resonant frequency ω_0 and its unloaded quality factor Q_0 [5, 6]. We measured the loaded electrical Q and the resonant frequency as a function of the probe position. The loaded electrical Q factor is related to the unloaded one, Q_0, by the expression:

$$Q = \frac{Q_0}{1+\beta_e}$$
$$\frac{1}{Q} = \frac{1}{Q_0} + \frac{1}{Q_{\text{ext}}} = \frac{1}{Q_0} + \frac{\beta_e}{Q_0}, \tag{1}$$

where β_e is the electrical coupling to the cavity. The electrical coupling is obtained from the reflection coefficient, which is a function of the input and reflected signals. These relations are shown by the following equations:

$$|\Gamma_0|^2 = \left(\frac{1-\beta_e}{1+\beta_e}\right)^2 \tag{2}$$

$$|\Gamma_0|^2 = \frac{P_r}{P_i} = \frac{P_i - P_{\mathrm{dis}}}{P_i}. \tag{3}$$

4. Experimental results

In figure 3 we can see the dependence of the cavity loaded electrical Q and the resonant frequency upon the probe position. It seems clear that the introduction of the probe decreases the cavity resonant frequency almost 1% down from the unloaded value of $\sim$14.92 GHz. This could be explained by the fact that the presence of the probe decreases the cavity inductance, which, in turn, raises the resonant frequency.

The loaded Q depends on the probe position, but in an unexpected way. We would expect a monotonic decrease of the coupling and, consequently, a monotonic increase of the loaded Q, with increasing distance of the probe from the end wall. However, for distances from the end wall above 0.9 mm the loaded electrical Q instead of continuing to increase starts to decrease. We think that the tapered section improves the impedance matching between the cavity and the coaxial transmission line, causing this reversion effect when the probe is approaching that section.

5. Conclusion

We have constructed a small cryostat to measure the loaded electrical Q and the resonant frequency as a function of the probe position inside a microwave re-entrant cavity. The operation of this cryostat required only about 10 l of liquid helium for each run, making our experiment fast and economic.

The results show that the frequency of the cavity is strongly dependent on the probe position inside the cavity, probably because the probe decreases the cavity inductance, which, in turn, raises the resonant frequency.

We also found an unexpected dependence of the loaded electrical Q on the probe position. We think that the tapered section improves the impedance matching between the cavity and the coaxial transmission line, causing this surprising behaviour when the probe is approaching that section.

Our results show that it is possible to obtain an unloaded Q as high as 200×10^3 for that cavity at 4.2 K, because the coupling for a 132×10^3 loaded Q measurement value was about 0.5; we believe that the unloaded Q can be increased by one order of magnitude when the cavity is operated at 0.1 K.

Acknowledgments

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