Superconducting cavity transducer for resonant gravitational radiation antennas

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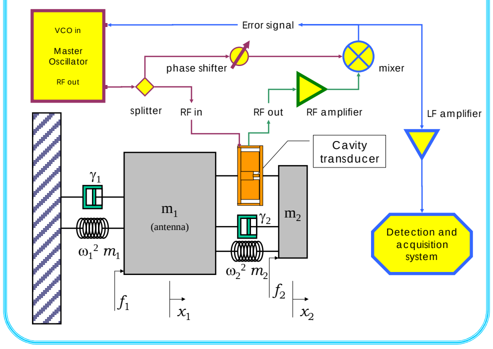
- Parametric transducers, such as superconducting RF cavities, can boost the bandwidth and sensitivity of the next generation resonant antennas, thanks to a readily available technology.
- We have developed a fully coupled dynamical model of the system "antenna-transducer" and worked out some estimates of signal-to-noise ratio and the stability conditions in various experimental configurations.
- We also show the design and the prototype of an RF cavity which, together with a suitable feedback electronic, will be used as a test bench for the parametric transducer.

Detector conceptual layout



Equations of Motion

Mechanical & E.M.

$$\begin{cases} \ddot{x}_1 + \frac{1}{\tau_1}\dot{x}_1 + \omega_1^2 x_1 - \frac{1}{m_1}\left(\frac{m_2}{\tau_2}\dot{\delta} + m_2\omega_2^2\delta + \frac{1}{2}CH^2 + f_1\right) = 0 \\ \ddot{\delta} + \frac{1}{\tau_2}\dot{\delta} + \omega_2^2\delta + \ddot{x}_1 + \frac{1}{m_2}\left(CH^2 - f_2\right) = 0 \\ \ddot{H} + \frac{1}{\tau}\dot{H} + \omega_0^2 H\left(1+C\delta\right) - \omega_0^2 f_{\omega_{mo}} = 0 \end{cases}$$

Single mechanical mode of the antenna

Relative displacement (secondary oscillator - antenna)

E.M. mode in the cavity

Dynamical back-reaction of the field radiation pressure on the masses

Coupling among the viscous dampings

Frequency modulation induced by the wall displacement

Master oscillator pump (locked through the feedback equations to the cavity's instantaneous frequency)

Feedback

$$\begin{cases} \omega_{mo} = \omega_{free} + k_{vco}\cdot V_{err} \\ V_{err} = -2G_{rf}\ k_{mix}\ \tau\ k_{cav}\ \frac{\beta}{(\beta+1)^2}\left(\omega_{mo} - \omega_{cav}\right) \\ \omega_{cav} = \omega_0\left(1 + \frac{1}{2}C\delta\right) \end{cases}$$

Master oscillator instantaneous frequency

RF amplifier and mixer gain

E.M. coupling: $P_{diss}/P_{in} = \beta$

Error signal (low freq.). Contains the information on the GW wave.

Cavity instantaneous frequency

The cavity act as a low-pass filter with respect to the modulating frequency Ω(GW wave):
$k_{cav} = k_{cav}(\Omega)$

δ oscillates at the same frequency of the driving force f_1:
$\Omega \ll \omega_0$

Cavity

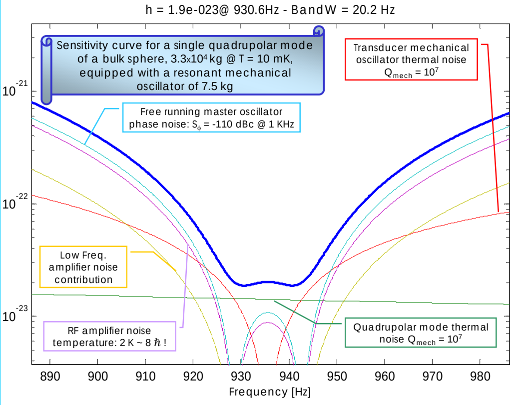
$$\begin{cases} \delta = x_2 - x_1 \\ C = -\frac{4\pi}{\omega_0}\frac{\partial \upsilon}{\partial x} \end{cases}$$

The cavity is sensitive to the relative displacement of the secondary resonator with respect to the antenna

The cavity is designed to have a very high frequency sensitivity to the wall displacement. Typically ≃ 10^{14} Hz/m

Expected performance

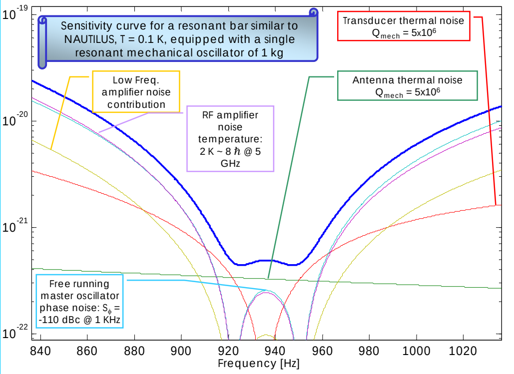
h = 1.9e-023@ 930.6Hz - BandW = 20.2 Hz



Massive, ultra-cryogenic spherical detector, as a possible development of the existing resonant antennas. The RF power dissipated in the cavity is as low as 1 μW. The table shows other relevant parameters used in this simulation.

Antenna mech freq.	935 Hz
Transducer mech freq.	935 Hz
$\partial\nu/\partial x$	10^{14} Hz/m
Cavity Q_0 ($\tau = Q_0/\omega_0$)	10^8

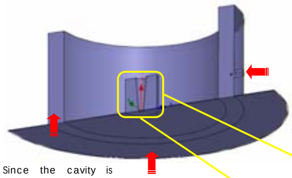
h = 4.4e-022@ 925.6Hz - BandW = 39.4 Hz



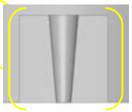
Antenna mech freq.	935 Hz
Transducer mech freq.	937 Hz
$\partial\nu/\partial x$	3×10^{13} Hz/m
Cavity Q_0 ($\tau = Q_0/\omega_0$)	10^7

NAUTILUS-like bar performance estimate in operating conditions. The RF power dissipated in the cavity is as low as 0.3 μW. The parameters used here are very reasonable, as they correspond to measured, available equipment.

The RF superconducting cavity



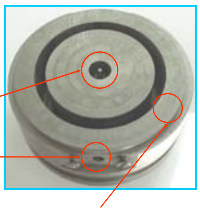
The RF power is coupled through the choke, so that the effects of the coupling on the frequency and the sensitive spot can be minimized.



Since the cavity is open, the chokes' shape and dimension are studied to minimize the radiated field, thereby preserving the e.m. quality factor Q_0.

The transducer oscillating mass will be made of Niobium and must be precisely machined and positioned to guarantee flatness and parallelism. The plate is *not* in contact with the cavity.

The cavity is made of bulk Niobium and is designed to operate at ~ 5 GHz. The theoretical maximum e.m. quality factor @ T = 1K, is $Q_0 \sim 10^9$. With a reasonable safe value of $Q_0 \sim 10^7 - 10^8$ and an input power of 1 μW, the electric field strength in the gap can be as high as 4×10^7 Volts/m.



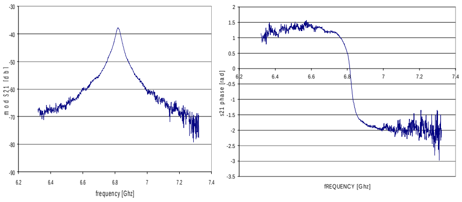
Top view of the superconducting, bulk niobium cavity, realized by our group. In this picture, the reference surface has been removed to expose the cavity sensitive spot.

The sensitive spot is a circular surface, 1 mm Ø, which is only 15 μm away from the transducer oscillating mass (gap distance).

The RF antenna enters the cavity through the choke

The surface shown here has not been chemically etched yet.

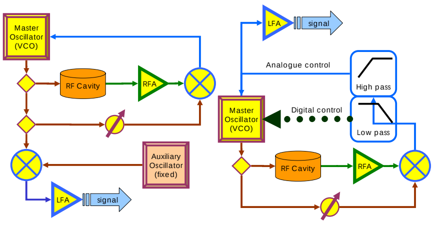
An aluminum prototype ready for testing. Note the clamps that keep the cavity tight onto the reference plane and the RF connectors that delivers the power and extract the signals. In this configuration we can test the cavity both in reflected power (one-port configuration) and in transmitted power (two-ports configuration).



Magnitude and phase of the transmitted power through a room temperature Nb cavity. The base frequency is higher than the design value due to the particular experimental setup, which presses the back-plate towards the cavity to ensure optimal electrical contact. This alters the gap distance, which does not comply to the nominal value anymore.
This experimental setup is used initially only to fully characterize the RF power couplings and the RF property of the choke and the cavity. The second step, will involve a variable distance back-plate, which will be tuned at cryogenic temperatures.

Work in progress

- Our present efforts are aimed to prove the performances of the cavity and the feedback electronics.
- We are now building an experimental setup to test a Niobium cavity in a temperature range 1 to 4 K, and a room temperature test-bench for studying the impact of gap and the reference plane.
- Since there are a number of possible implementations, we will study which electronic readout will prove most effective. The conceptual diagram of alternative, more sophisticated readouts is shown hereunder:



- Once the detection electronics is under control, the system can be mounted with the transducer on a small antenna, on which we will test the transducer-antenna interaction and calibration.
- Testing and characterization of optimal electronic components will continue to ensure reliability and to study possible redundant solutions to failure in critical components (e.g. RF amplifiers, see poster #53: "Gain and noise analysis of HEMT amplifiers from room temperature to superfluid He").

Conclusion

- The parametric conversion shifts the detection problem to a very high frequency range, where many noise sources can be made negligible.
- The implementation of high frequency electronics has the advantage of a reliable and well developed technology, which exhibits near-SQL behaviour in available commercial components.
- Although we understand that the fundamental, physical limits of a parametric transducer are comparable with those of an ordinary capacitive transducer, the parametric one can have technological advantages over a SQUID-based readout.
- Works in progress to optimize the feedback control loop as well as the implementation with the antenna.