NEW PARAMETRIC TRANSDUCER FOR RESONANT DETECTORS: ADVANCES AND ROOM TEMPERATURE TEST*

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Abstract. We are developing a prototype of cryogenic parametric converter transducer operating at 5 GHz, for the upgrade of the ROG Collaboration resonant G.W. antennas. This device is built on the experience of the Niobe detector (D.G.Blair et al.), with substantial modifications that should let us achieve better stability and sensitivity. The prototype uses as parametric converter a superconducting coaxial cavity with a 50 micron gap (\(Q_0 = 5 \times 10^8\) at 1.5K and 100\(\mu\)W RF power dissipation), and a contactless RF coupling for thermal insulation between the 2K stage and the ultra cryogenic (100 mK) antenna. The coupler features a constant transmission loss of 0.2 dB over a range of displacements of \(\pm 5\) mm in x, y and z around the nominal operating position with a separation of 8 mm between the two halves of the coupler. In this way the large, low frequency swings (0.5 and 17 Hz), of the 2 Tons antenna around its suspension point have no influence on the transducer performance. To test all the components of the transducer and the system performance, a room temperature prototype is installed on the TART (Test Antenna at Room Temperature) facility at the INFN labs. Using critical coupling for the RF cavity input coupler we manage to keep to a minimum the leakage of the drive signal to the first RF amplifier. In this way we avoid degradation of the RF amplifier noise figure (0.6 dB at room temperature) produced by the RF amplifier saturation. Experimental results agree with the full analysis of the room temperature detector performances.

1. Introduction

RF parametric converters are self-calibrating wide band transducers suitable for gravitational wave antennas.

Previous efforts in this direction include the transducer at 10 GHz successfully operated on the Niobe Antenna [¹].

For the “Mario Schenberg” omni directional spherical detector, the Brazilian group is developing 6 parametric (X-band) transducers [²].

Our group is studying a parametric radio-frequency converter to be used as transducer in the ROG acoustic gravitational wave detectors, to replace the high field DC capacitance used nowadays [³]. This transducer is based on non-linear transfer of the energy, stored in a high \(Q\) factor resonant cavity, caused by the frequency variation of the cavity produced by fluctuations of cavity dimensions.
The core of the transducer is a superconducting re-entrant cavity resonating at 5GHz with a gap of 50μm. The cavity gap is modulated by the motion of the auxiliary resonator m2 producing a frequency shift of the cavity resonance. Such frequency change is translated to the Master Pump Oscillator (MPO) of the parametric converter via an Automatic Frequency Control (AFC) feedback loop. The frequency modulation of the MPO produces sidebands at the antenna frequencies: this is the output signal from the transducer.

2. Cavity

The superconducting RF (SRF) cavity is the active element of the transducer. Simple Man computation on the cavity shape (based on lumped circuit model) would suggest using a pump frequency f0 as high as possible, and a cavity gap x as small as possible.

For a lumped LC resonator the rate of frequency deviation produced by the change of the capacitor gap is proportional to the resonant frequency f0 and inversely proportional to the capacitor gap x.

SRF considerations, RF losses, proportional to f0^2, according to the Bardeen Cooper and Schrieffer (BCS) theory, and residual (non BCS) losses in the 10nW range, call for the lowest end of the 5-10GHz frequency band. Electromagnetic considerations also suggest the lower limit of the 5-10GHz band to better match the lumped circuit approximation giving a better \( \frac{df}{dx} \).

Mechanical considerations on cavity construction call for cavity dimensions in the 3-5mm range. As a trade-off between different requirements we chose a coaxial cavity operating at the nominal frequency of 5GHz loaded by the parallel plate capacitor (2mm in diameter and a 50μm gap) formed by the end of the central conductor and the face of the transducer resonator (figure1).

![Figure 1, cavity body](image)

The measured cavity sensitivity was 33MHz/μm, in agreement with the value of 34MHz/μm given by numerical solution of the fields. After a light chemical polishing (removing ten microns) using a standard Buffer Chemical Polishing (BCP) acid solution and a thermal annealing of the niobium at 1650°C for 15 hours at a pressure of 6×10^-8 torr, we measured an electric quality factor \( Q_0 = 5 \times 10^8 \) at 1.5K, with an input power of 100μW, at the frequency υ = 5.3581GHz.
3. **Wireless Feed Line (WI-FI)**

To couple the RF signal to the cavity with minimum signal attenuation, to prevent the transmission of unwanted mechanical noise and to keep to a minimum the heat load on the cryogenic GW antenna, we developed, as the last stage of the feed line, a contactless RF coupler to be inserted between the inner shell of the cryostat and the transducer cavity. The goal is to have a system with transmission losses lower than 0.2–0.3 dB not to impair the noise figure of the system.

The coupler is designed to operate at a nominal distance of 8 mm between the two halves.

To cope with the large low frequency oscillation of the antenna (0.5 and 17 Hz), the coupler must withstand, without significant transmission losses, alignment changes up to 5 mm in any direction from the optimal operating position.

The plot in figure 3 shows the measured transmission losses (in dB) of the coupler for a combined axial (X) and transverse (Y) displacement of ±5 mm. In this way the system can compensate low-frequency oscillations of the bar around its center of mass.

The WI-FI coupler (shown on figure 3) is a circular wave guide working at 5 GHz. The wave guide is built on aluminum, the inside RF antenna is copper insulated by a Teflon™ sleeve.

The circular wave guide works in TM_{0,1} mode with the cut off frequency \( \nu_c \) at about 4 GHz.

The radius \( r \) of the guide is \( r = \frac{c \times u}{2\pi \times \nu_c} = 30 \text{ mm} \) where \( c = 3 \times 10^{10} \text{ cm/sec} \) is the speed of light in vacuum and \( u = 2.405 \) is the first root of the \( J_0 \) Bessel function. The guide has a Choke flange to reduce signal losses due to free space radiation at the gap. For signals with wavelength \( \lambda = 60 \text{ mm} \) we need a depth of the choke coupler of \( \frac{\lambda}{4} = 15 \text{ mm} \). Furthermore the distance between the centre of the connector and the wall of the guide has to be about \( \frac{\lambda}{4} \) too. In this way we have a zero field value inside the choke, with minimum signal leakage. Transmission measurements at 5 GHz, changing the distance of the two halves of the WI-FI and shifting their axes, give the results shown in figure 3.
We started by the working point, with the two halves spaced by 8\,mm, and shifted it in each direction with 1.2\,mm step, overlaying 12\,mm \times 12\,mm area. The X axis gives the distance between the two WI-FI halves, while Y axis is the skew from the centre. The working point is (6;6) coordinates, that means 8\,mm distance and complete alignment.

4. Electronics

The RF signal coming from the MPO is split in two parts. The first part is amplified and sent to the cavity through a circulator. The reflected power, exiting the cavity, is coupled to the third port of the circulator, amplified by a low noise amplifier (0.6\,dB noise figure) and enters a mixer. The signal coming from the MPO through the second branch of the 3\,dB hybrid is used as local oscillator of the mixer. This signal is shifted out of phase by 90^\circ from the RF signal reflected by the cavity. The IF
output of the mixer is the amplitude of the quadrature component of the signal reflected from the cavity.

This amplitude is proportional, around the resonance, to the phase shift introduced in the reflected power. The phase shift is negative for cavity frequency lower then the generator frequency and positive for the opposite situation, null when the two frequencies are the same.

Operating the cavity at the resonant frequency and RF critical input coupling (matched load condition), the reflected power is zero. In this way we will avoid degradation of the RF amplifier noise figure, coming from RF amplifier saturation experienced in similar transducers [5].

Mechanical vibrations of the antenna change the resonant frequency of the cavity and so the reflected power. The phase of the reflected signal is proportional to the frequency difference between the cavity’s resonant frequency and the frequency of the RF generator. The reflected signal contains the information (frequency and amplitude) coming from the mechanical vibrations of the antenna.

5. Room Temperature Test Facility (TART)
Most features of this transducer (with the exception of the high Q) can be tested at 300K. For this purpose we installed this transducer on the TART (Test Antenna at Room Temperature) facility in the INFN labs at the University of Roma Tor Vergata: it consists of a fast opening vacuum chamber (4.5 m long and 1.5 meters in diameter), hosting a close replica of the Nautilus antenna: an Al 5056 bar, 3 m in length and 60 cm in diameter and a simplified version of the suspensions: a Ti cable (9 mm diameter) hanging from a massive steel ring that rests, in turn, on a four point canteliver cradle.

The facility is equipped with piezoceramics at the bar center and at quarter length (to excite the second longitudinal mode) and accelerometers.

The cavity measures the relative displacement between the antenna and a secondary mechanical oscillator. The secondary oscillator is the ROG usual rosette design, built in Al 5056 by electric discharge (ED) machining, with m_s=2kg (for bandwidth) and a vibrating surface of 174 cm². The resonator is tuned to the antenna frequency by properly adjusting the thickness of the “rosette arms”.

In the cryogenic transducer a layer of ~1.2 µm RF grade Niobium will be deposited on the vibrating surface facing the cavity; this is being done at the CERN facilities of the AT-TS division, group MME. The Niobium layer is deposited on the whole face of the “rosette plate” to keep to a minimum the RF losses of the system. The mechanical system shows two modes at 832 and 873 Hz.

![Graph](image_url)

Figure 5, noise spectrum of the Antenna and the TART facility

The measured sensitivity versus frequency of the transducer is given in the figure below.
At room temperature, with low mechanical $Q$ factors, we achieved a sensitivity of $5 \times 10^{-19} \left[ \frac{1}{\sqrt{Hz}} \right]$ at about 870 Hz.

6. Conclusions
Three 5 GHz SRF cavities have been built with the characteristic of maximize the energy transfer and the sensitivity of the transducer system. After niobium surface treatment the electromagnetic quality factor reached the value $Q_0 = 5 \times 10^8$ at 1.5 K.

With the WI-FI system the signal is transmitted with a small power leakage to the external electronics without introducing additional noise.

These two devices and the RF electronic circuit were tested on the T.A.R.T. antenna obtaining good results at room temperature. The plot in figure 6 shows the spectral strain sensitivity $S_h$ of the TART 300 K set-up. The system sensitivity is better than $10^{-18} \left[ \frac{1}{\sqrt{Hz}} \right]$ in the frequency range 825 – 880 Hz, the peak sensitivity is $\sim 10^{-19} \left[ \frac{1}{\sqrt{Hz}} \right]$. The peak at 848 Hz is a calibration signal injected on the antenna through a piezo crystal.

The excess broadband noise between the two modes is due to the poor feedback gain in the AFC loop locking the RF Oscillator to the cavity resonant frequency.

By a proper design of the AFC Feedback loop we can reduce the contribution of the phase noise of the master oscillator by a factor 10 at least.

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