Heated Cryogenic Load in Q band (33-50 GHz) Waveguide for Precision Noise Measurements

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1. Introduction.

Until now, the cryogenic measurements of Q band amplifiers have been performed in the 1020-1 cryostat of the Yebes laboratory. In the case of devices with coaxial input, two different methods are in use:

1) Cold attenuator method [6][7][9].
2) Heated load method [8] (using a mGaAs MMIC from IAF which includes a well matched 50 Ω termination, the heating element and an on-chip temperature sensor).

The cold attenuator is very usefull because it allows taking advantage of the automatic control of the noise diodes by the noise figure meter. This makes near real time tuning of the amplifier bias for minimum noise possible. The heated load provides higher accuracy since the calibration depends only on the physical temperature (measured) of the load, but it is much slower and is not very practical for tuning.

In the case of LNAs with waveguide input, the typical measurement method involves the use of the classical hot/cold loads (ambient/LN2). In this case a window is attached to the cryostat and the amplifier is mounted inside with a short, low loss feed horn attached to the input. This method has demonstrated a good accuracy [2] but it is very time consuming and inconvenient, since it needs LN2 (not always available in our lab) for cooling the microwave absorber. Other problem of this method is that due to the use of two different input teminations, the change of reflection coefficient may easily introduce ripples in the measurement.

Other more convenient possibility for LNAs with waveguide input is using a variable temperature heated load in waveguide. This device is simply a waveguide matched termination fitted with a heating resistor and a temperature sensor. The load can be connected to the amplifier using a short section of thin wall stainless steel (SS) waveguide which provides thermal isolation and prevents changing the temperature of the amplifier when the heating resistor is switched on. However, the length of the stainless steel waveguide should be kept as short as possible since its insertion loss causes a small reduction of the effective noise temperature presented at the input of the amplifier (cooling effect).

This report presents a design of a waveguide heated load. It is expected to be a practical and convenient alternative to hot/cold loads method, with no need for LN2, improved accuracy and reduced ripple.

2. Fabrication of the waveguide heated load.

The heated load is a rectangular WR-22 waveguide milled in an aluminum split block with an absorber inside. The absorber is machined with a wedge shape, tapered in two directions from a rectangular bar (Figure 1). Two faces of the absorber are directly glued[1] to two sides of the waveguide to improve the thermal contact. The block also incorporates a housing for a cartridge heater[2]. The temperature is sensed with a diode attached to the waveguide.

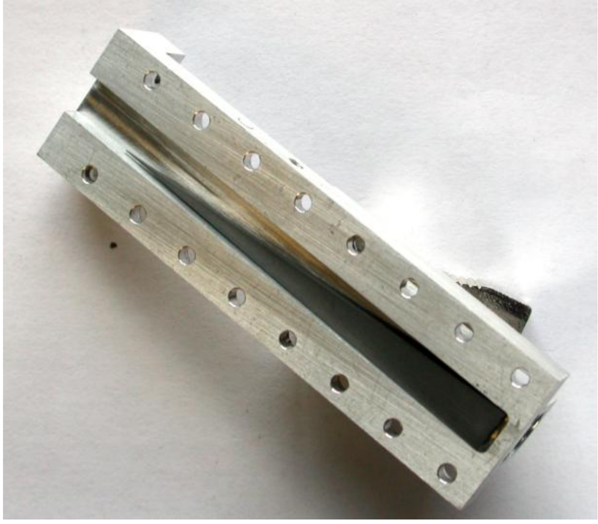

Figure 1. Wedge shaped absorber inside the WR-22 waveguide split block. This design is similar to the one used in [3].

The absorber must be sufficiently long so that a low amount of energy reaches the base mounting plate where it could be reflected back into the line. In the *Termination Design Considerations* of the MF Technical Bulletin, ECCOSORB [4] recomends a length-to-base-width ratio of 10:1 for a VSWR lower than 1.01 over the full waveguide frequency band. Following this rule, a length of 57 mm is required for the WR22 waveguide dimensions, 5.69 x 2.84 mm. The material of the absorber is the ECCOSORB MF-117, a magnetically loaded epoxy, widely used for terminations.

The specific heat of OFHC copper at cryogenic temperatures (10 - 60 K) is no lower than half the value of the aluminum 6061 [10], and three times denser. Therefore it is reasonable to assume that OFHC copper has a higher heat capacity, so aluminum 6061 was selected for the fabrication of the split block. A lower heat capacity[3] translates in less time required to change the temperature of the load. The total mass of the aluminum split block is 30.6 gr. In addition, the SS screws contribute with an additional 3.1 gr. and the cartridge heater with another 4.1 gr.

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[1] *The epoxy used to glue the absorber to the waveguide is Scotch-Weld EC2216.*

2 Cartridge heater of 50 Ω, 50 W, for cryogenic applications (part number HTR-50 from Lake Shore)

3 The heat capacity is the amount of heat needed to raise the temperature of an object by 1ºC. The heat capacity depends on the properties of the particular material (specific heat) and it is directly proportional to its mass.

To thermally isolate the DUT from the heated load, a stainless steel[4] waveguide 50 mm in length (brass flanges included) is connected between them. The length of SS waveguide is selected as a trade-off between thermal conductance and attenuation. For a DUT at 15 K and the heated load at 50 K, the thermal power transmitted to the DUT by the SS waveguide is 12 mW [5]. This power is similar to the power dissipated in the DUT for a typical amplifier. The average attenuation (0.23 dB, in the 33-50 GHz band) produces a slight reduction of the equivalent output noise temperature of the heated load[5] (49.26 K instead of 50 K). If no correction is applied, the error for assuming the physical temperature of the load as the equivalent output noise temperature after the SS waveguide is of 1.5 %. A more detailed analysis of thermal conductivity and electrical losses of thin wall millimeter wave stainless steel waveguides can be found in [5].

3. Thermal performance of the heated load.

Noise temperature measurements involve data acquisition of the output noise power for two different physical temperatures of the input termination. Ideally the temperature of the input load should be switched as fast as possible to reduce possible measurement errors which may appear if the gain of the system (amplifier and receiver) changes or drifts between the two noise power measurements. In order to speed up the process it was decided to use a cryogenic PID (Proportional, Integral and Derivative) temperature controller with two independent loops. One of the loops is dedicated to keep the temperature of the cold plate constant at 15 K, while the other stabilizes the temperature of the heated load at the selected set point (either 20 or 50 K). The heated load is connected by a weak thermal link to the cold plate for refrigeration. Note that the cold temperature set point (20 K) is not the coldest temperature achievable (ideally 15 K). The reason for this is to avoid the excessive time which it will take for the system to reach the equilibrium in that case due to the exponential decay.

The thermal performance has been evaluated by measuring these parameters:

1. Time and power required to stabilize the load at the hot set point (from 20 to 50 K).
2. Time and power required to stabilize the load at the cold set point (from 50 to 20 K).

All tests were performed with the heated load connected to the SS waveguide required for noise temperature measurements. The end flange was fitted to a L-shaped gold plated copper piece in good thermal contact with the cold plate of the cryostat, as it is shown in Figure 2. The temperatures of the load and the copper strap were monitored with diode sensors. One or two cooper braids[6] were used to reduce the thermal resistance of the heated load to the cold plate. This improves the cooling speed (since the thermal time constant is reduced) at expense

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[4] *The stainless steel used to make the waveguide is AISI 304 (Fe/Cr 18/Ni 10). The X-ray measurement of this SS made in Yebes shows a 70.9 % Fe, 18.5 % Cr, 8.6 % Ni, 1.7 % Mn.*

[5] *Assuming a non-linear physical temperature distribution in the heated load ([5]-Appendix III).*

[6] *The material of the braid is cooper OFHC with a section of 1.7 mm^2. The braid is 125 mm long.*

of requiring additional power to achieve the desired hot temperature. The heater power is controlled by a PID[7] algorithm, implemented in the Lake Shore model 336 Temperature Controller. Table 1 presents the basic configuration parameters used in the controller.

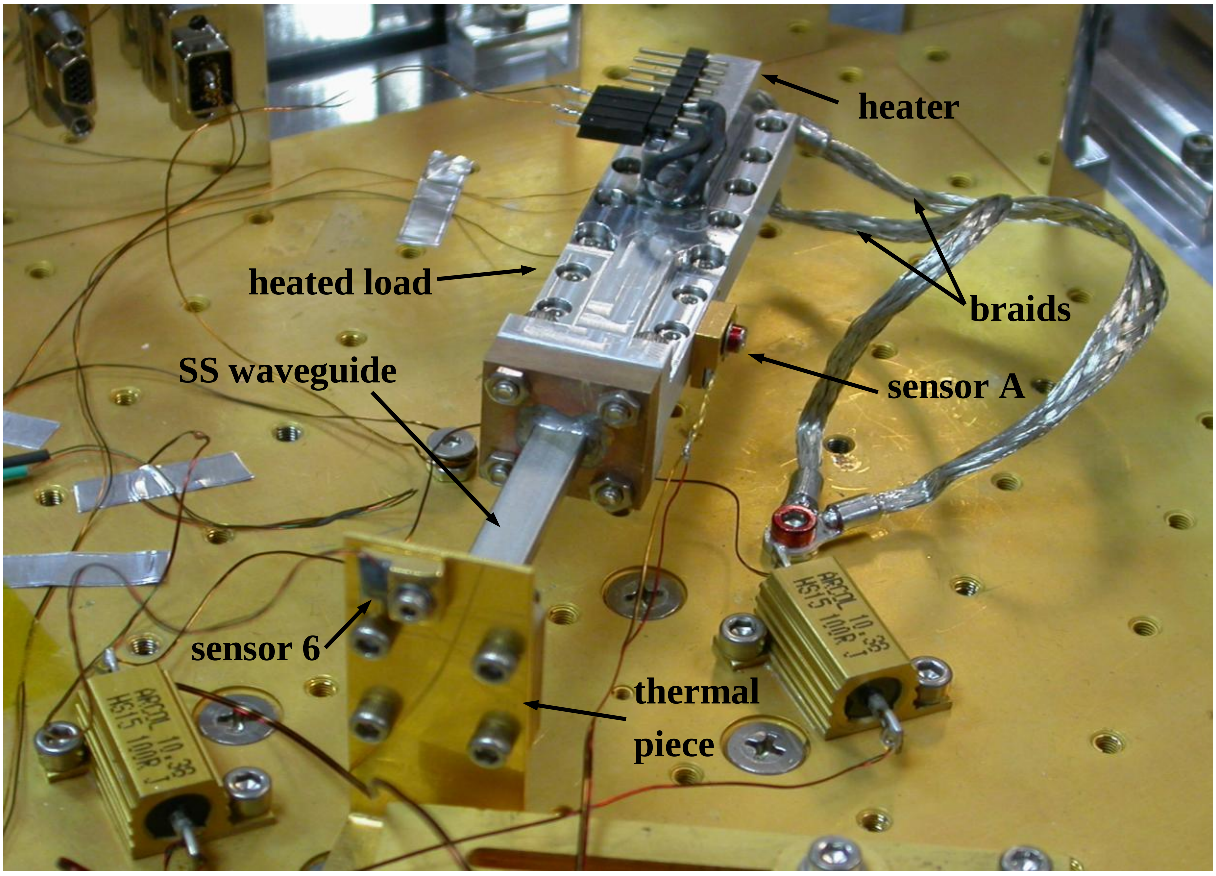

Figure 2. Setup for the heated load thermal test.

Table 1. Basic configuration parameters of the port "Output 1" of the 336 Temperature Controller used to connect it to the heater.

Parameter	*Data*
Heater resistance	50 Ω
Max. current	0.707 A
Input control	Sensor A
Mode	Close loop PID
Ramp	Off/ 10 Kmin^{-1} / 20 Kmin^{-1} / …

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[7] The PID loop parameters where obtained by using the auto-tune feature of the Lake Shore 336 Controller at 40 K.

Some conclusions which were inferred from the thermal tests are:

- The cooling speed is the dominant factor in the total measuring time. It is inversely proportional to the thermal resistance to the cold plate. It can be controlled in practice by the length and number of copper braids used.
- The heating speed can be highly increased by using the PID controller if sufficient open loop power is available (25 W in our case). However, it is limited by overshooting. This effect can be avoided by changing the set point smoothly using a linear ramp. The value of the ramp should be chosen to optimize the speed, avoiding a large overshoot.
- It was considered that an acceptable compromise between speed and power dissipation was obtained with two copper braids (Figure 3). The power required to maintain the load at 50 K was 830 mW. With a good selection for the ramp (30 K/min) the load can be stabilized at the hot set point (50 K) in less than 3 min. After warming (50 K), it takes ~7 min. to stabilize the load at the cold state (20K). Obviously, the limiting factor is the cooling speed.
- With the previous conditions (2 braids), an increase of 0.03 K was registered in the sensor attached to the L-shaped piece when the heated load set point was switched from 20 to 50 K. Note that the temperature of the cold plate was well stabililized to 15 K by an independent control loop. The reason for this effect is the non cero thermal resistance between the L-shaped piece and the cold plate.

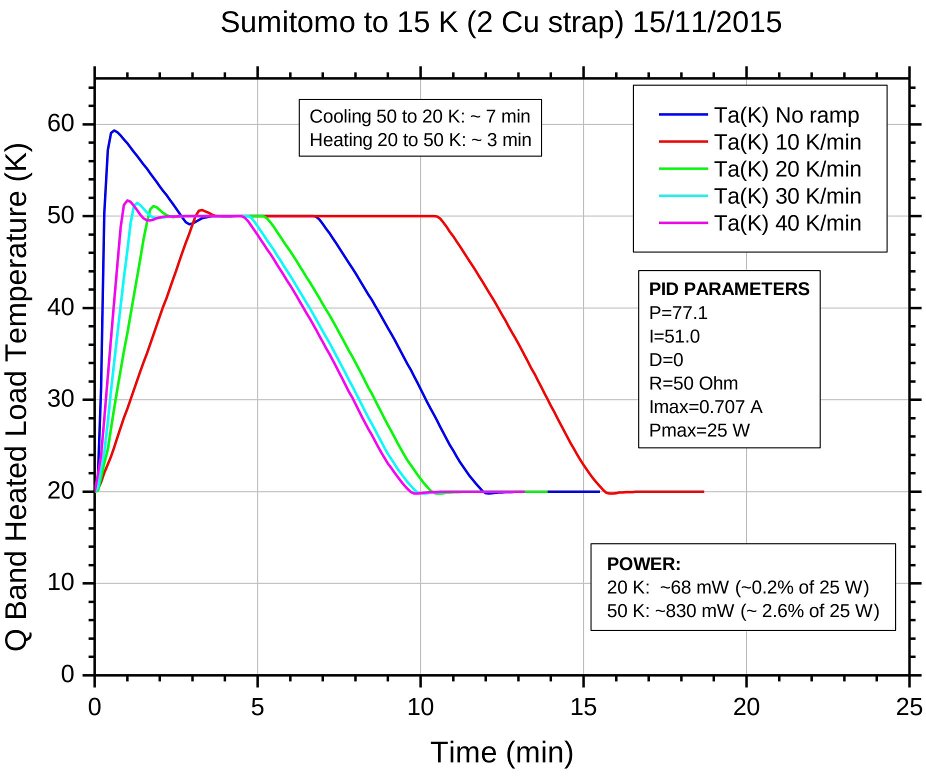


Figure 3. Thermal response of the heated load with two identical braids. A ramp of 30 K/min is the best option to minimize the heating time. This is the configuration used for the noise measurements presented in this report.

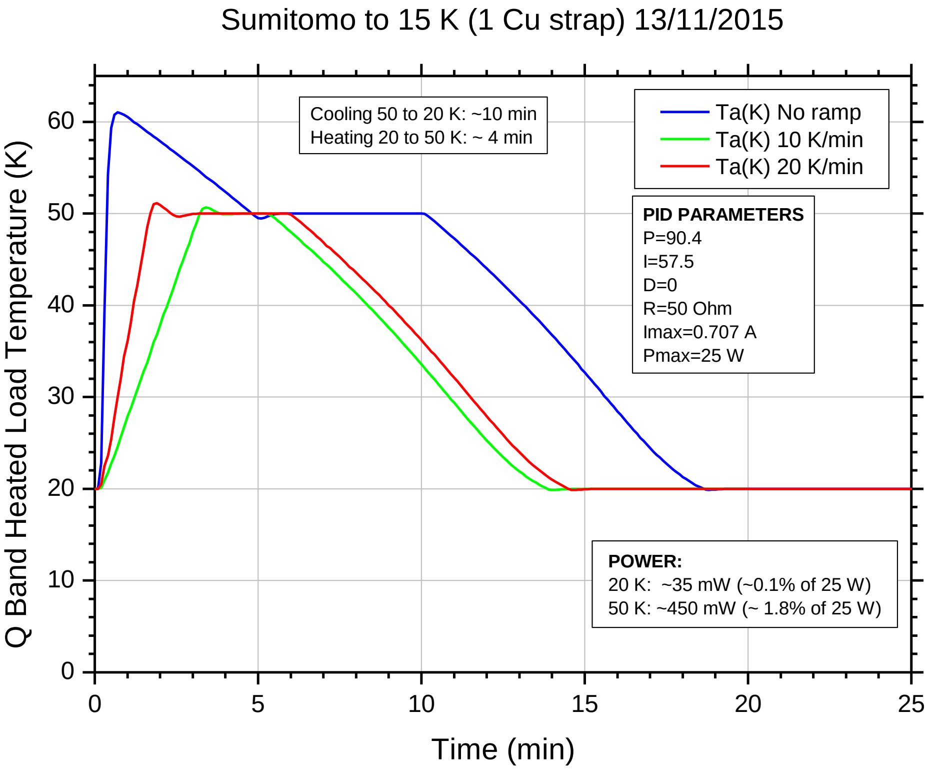


Figure 4. Thermal response of the heated load with only one braid connected to the cold plate. A ramp of 20 K/min is the best option to minimize the heating time. Note the much longer cooling time respect to Figure 3.

4. Input reflection of the load.

Input return losses measurement (Figure 5) was performed at ambient temperature using the PNA E8364B (Agilent) and a TRL calibration[8] between the two 2.4 mm coaxial to waveguide adapters (HP Q281A and Q281B). The reference plane of the calibration is the waveguide flange of the adapters (UG-383, round) and it did not include the additional UG-383 (round) to UG-599 (square) flange adapter[9] needed to connect the heated load.

Note the excellent results obtained and the slight degradation observed when including the SS waveguide. The return loss is not expected to degrade when the device is cooled to cryogenic temperature since the design does not depend critically on the particular parameters of the absorbing material.

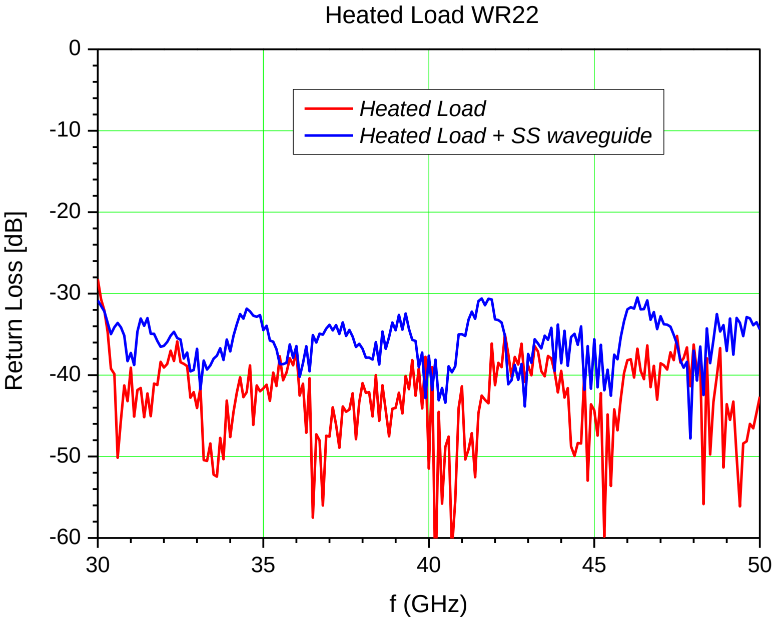
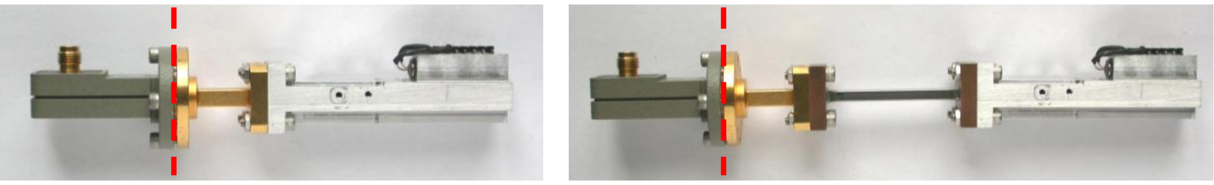


Figure 5. Return losses of the heated load in WR22. The reference plane of the calibration of these measurements is marked with a red dash line in the photos a)b):



a) Measurement of the return losses of the heated load (red line in Figure 5)

b) Measurement of the return losses of the heated load plus SS waveguide (blue line in Figure 5).

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[8] *The calibration was stored as "WR22_p1_to_WR22_p2_200pt_TRL_0413" and it is associated to the state "Q band WR22 TRL.cst"*

[9] *Quinstar QFA-Q383599.*

5. Noise measurements with the Heated Load.

The heated load was validated by performing cryogenic noise measurements of a Q band amplifier (YMQA 1006 4[10]) with waveguide input/output (square flange). It is interesting to note the reduction of the cooling time with respect to the thermal performance test from 7 to 4 min. This is very likely caused by a different tightening of the bolt attaching the braids to the load.

Comparison with LN2 measurements

The heated load configuration used is described in Figure 3. The hot and cold set points were 50 and 20 K respectively and two copper braids were connected to the cold plate at 15 K to improve the cooling speed. The results are compared with previous noise measurements obtained using a short horn with ambient and LN2 absorbers. Figure 6 and Table 2 present the results of the comparison. The main feature observed is the drastic reduction of the noise ripples with the new heated load. The average noise is ~1 K (~5%) lower with the new method (see Table 2).

Table 2. Comparison of the average noise temperature obtained in the 33-50 GHz band with ambient/LN2 absorbers and with the heated load.

Measurement	*T mean (35-50 GHz)*
Horn: Ambient/ LN2 loads	18.28
Waveguide Heated load	17.17

Repeatability

The repeatability was checked by performing three independent heated load noise measurements of the YMQA 1006 4 amplifier. The results are presented in the Figure 7 and in Table 3. The variation of the average noise temperature within the measurements is less than 1%.

Table 3. Repeatability test: three independent values of the average noise temperature of the YMQA 1006 4 amplifier obtained with the heated load.

Measurement	*T mean (35-50 GHz)*
Heated load 1	17.17
Heated load 2	17.28
Heated load 3	17.25

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[10] *Test performed on YMQA 1006, a 35-50 GHz MMIC amplifier prototype for the ALMA project with WR22 waveguide ports (square flange). Cryogenic bias used: (0.6 8 0.28) (0.55 8 0.29) (0.8 16 0.28) (0.7 8 0.27).*

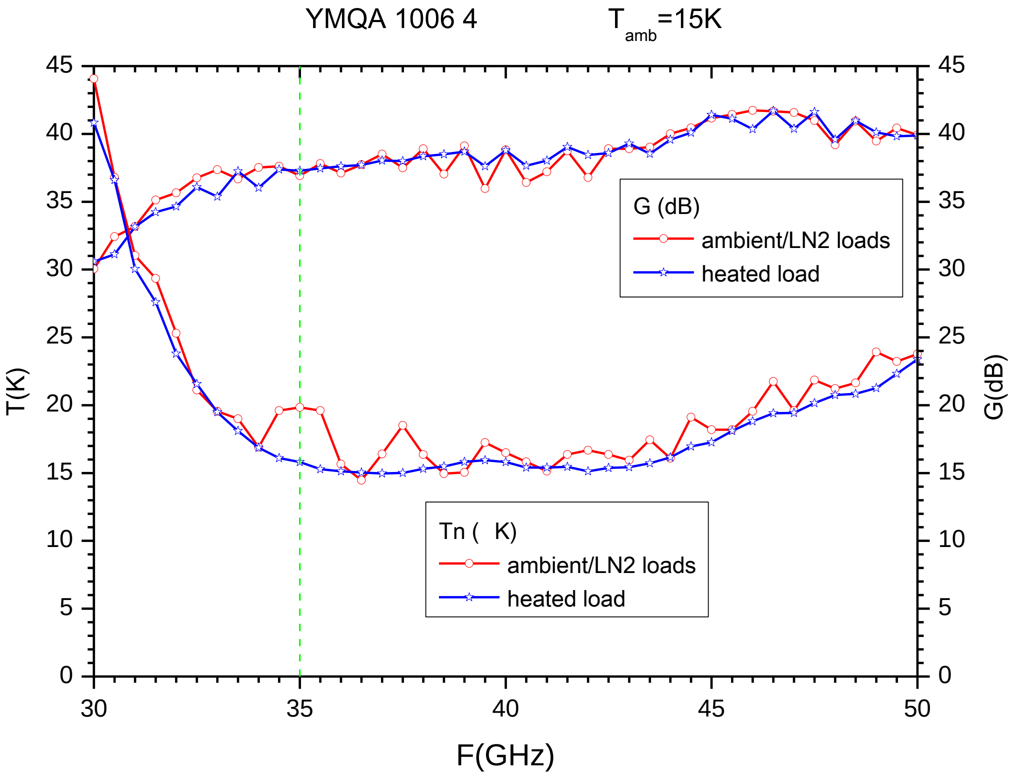

Figure 6. Comparison of the measurements of gain and noise temperature of the YMQA 1006 4 amplifier using the heated load (blue line) against the measurement using ambient/LN2 absorbers (red line).

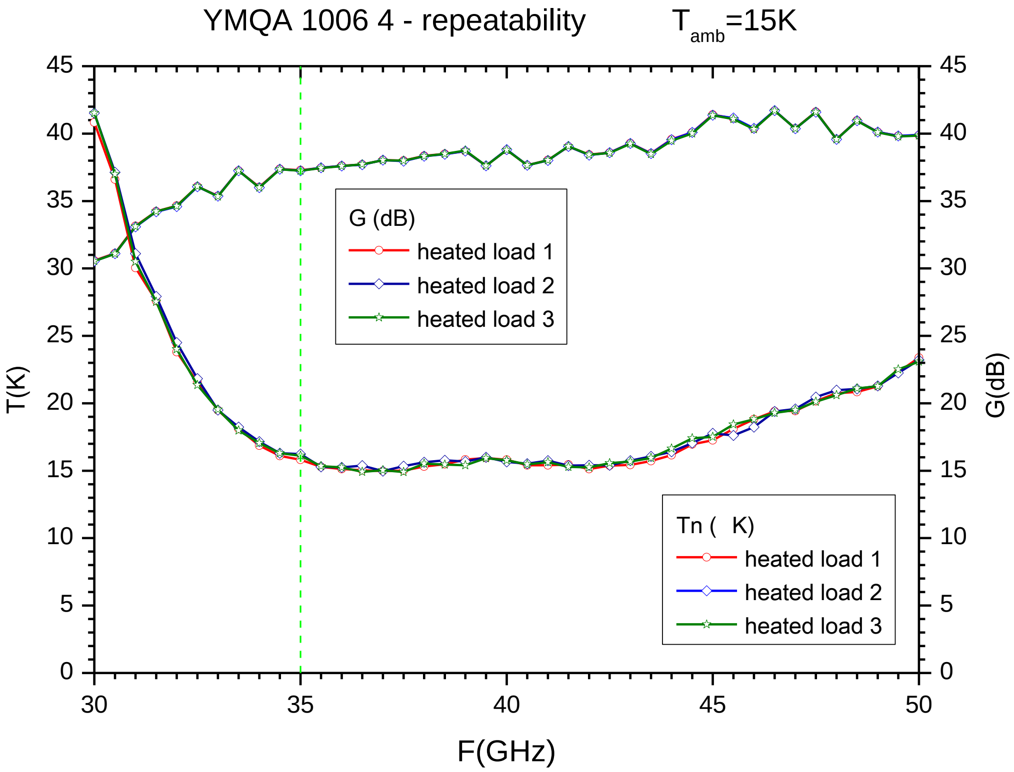

Figure 7. Comparison of three independent measurements of gain and noise temperature of the YMQA 1006 4 amplifier using the heated load (hot/cold set points of 50/20 K).

Correction of the hot temperature by the loss in the SS waveguide.

The effect of the loss of the stainless steel waveguide between the amplifier and the heated load has to be carefully taken into account if ultimate accuracy is desired. A rigorous calculation of this effect involves not only the loss, but also the temperature distribution along the waveguide. This contribution has been estimated using the methods presented in [5]. The result for a 50 mm long SS waveguide with the boundary conditions of 15 and 50 K of temperature respectively on each side is that the calculated mean effective noise temperature presented at the input of the amplifier in the 33 - 50 GHz band is **49.26 K** (a reduction of **0.74 K** respect to the physical temperature). **Note that if the correction is not applied, the noise temperature result will be systematically overestimated**. Figure 8 shows an example of the noise results obtained with and without correction for the YMQA 1006 4 amplifier. The corrected average noise temperature is **0.77 K (4.5 %)** lowers than the uncorrected value. Note that for the previous comparison with the measurements with ambient/LN2 absorbers this correction was not applied. The result obtained with the correction will be even more optimistic than the values presented in Figure 6 and Table 3.

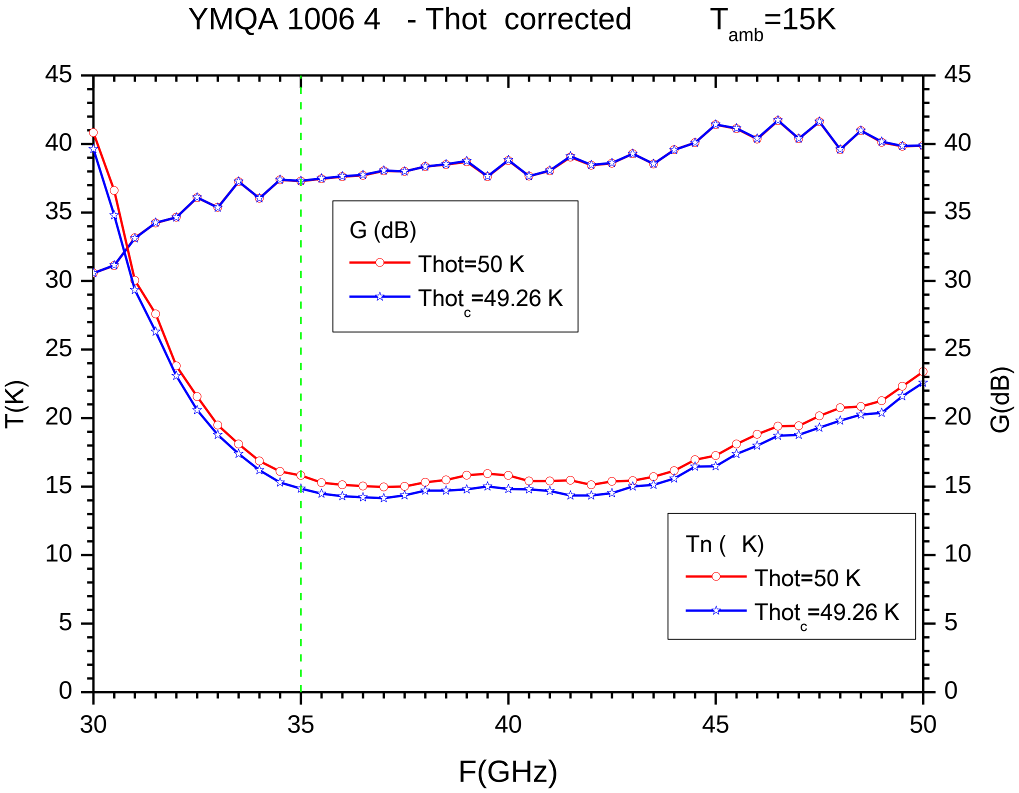

Figure 8. *Difference in the noise and gain measurement of the YMQA 1006 4 amplifier with and without the correction (see text) of the hot temperature of the heated load: The average noise temperature obtained with the correction is 0.77 K lower (T_{mean}=17.17 K with T_{hot} 50 K and T_{mean}=16.40 K with T_{hot} 49.26 K).*

Effect of different hot temperature values.

All the measurements presented previously were performed with the hot and cold temperature of the load set to 50 and 20 K respectively. Ideally the noise measurements should be independent of the values chosen for the hot and cold temperatures (although the accuracy may be dependant of their values for several reasons). In order to check the ideality of the method, a set of measurements was performed keeping the cold temperature constant but with different values of the hot temperature (35, 50 and 80 K). Figure 9 and Table 4 compare the noise temperature results obtained for the YMQA 1006 4 amplifier for the different values. The average noise temperatures values differ less than 1%.

Table 4. Comparison of the average noise temperature obtained using different values of the hot set point. The cold set point was 20 K in all cases.

Hot set point	*T mean (35-50 GHz)*
T_{hot} = 35 K	17.225
T_{hot} = 50 K	17.21
T_{hot} =80 K	17.29

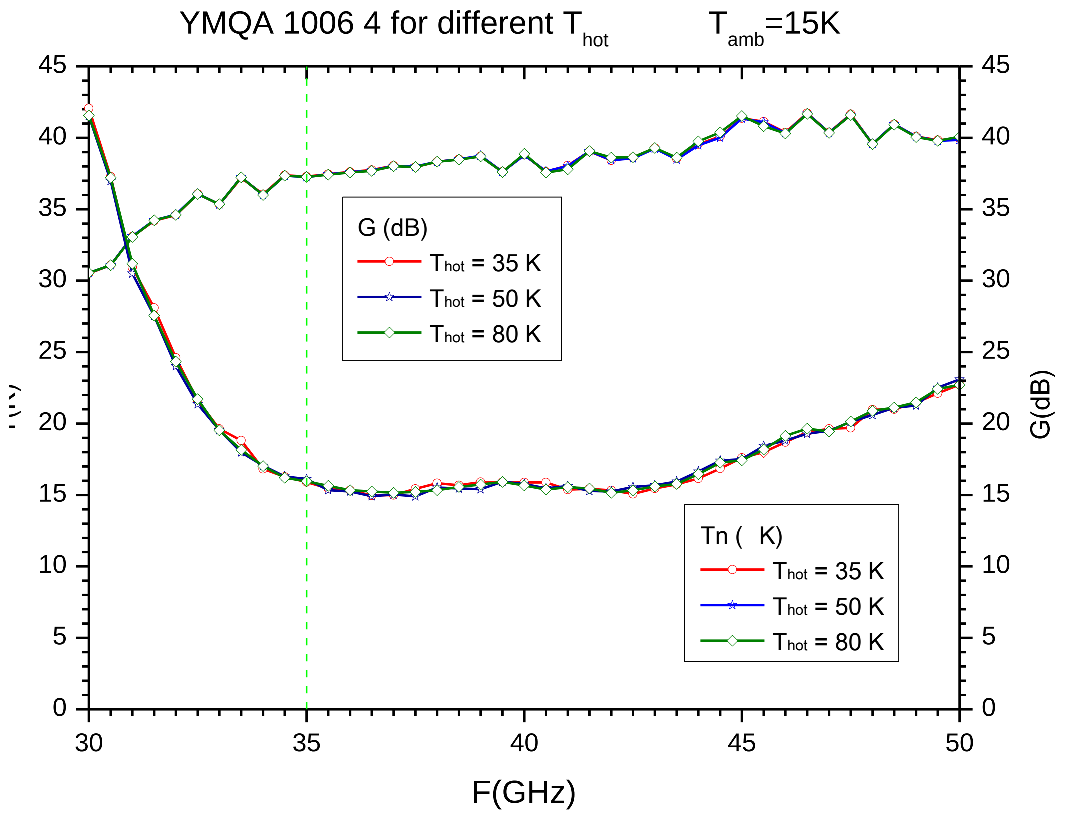

Figure 9. Comparison of the gain and noise temperature obtained using different values of the hot set point. The cold set point was 20 K in all cases.

Effect of changes in the amplifier physical temperature.

One side effect of the power delivered to heat the load is to produce a small change of the physical temperature of the amplifier. This effect should be small, since the temperature of the cold plate is well stabilized to 15 K, but as the thermal resistance between the amplifier and the plate is not null there is a measurable effect. In the measurements performed in this work, the increment of physical temperature measured in the amplifier was **ΔT=0.5K** (with set points of 20 and 50 K for the heated load). There was the concern of whether this change could affect significantly to the gain of the amplifier (which is assumed constant) and translate into an error in the noise temperature measured. In order to check if this effect could be significant, a new measurement was performed adjusting the set point of the cold plate (15 K) to compensate for the change in the temperature of the amplifier when the load is switched to the hot state. With the compensation, the temperature change of the amplifier was reduced to **ΔT=0.001K**. Figure 10 shows the comparison of the two measurements. The difference in the average noise temperature measured is less than 1%. It was concluded that the change of temperature of the amplifier did not affect significantly to the noise temperature measurement.

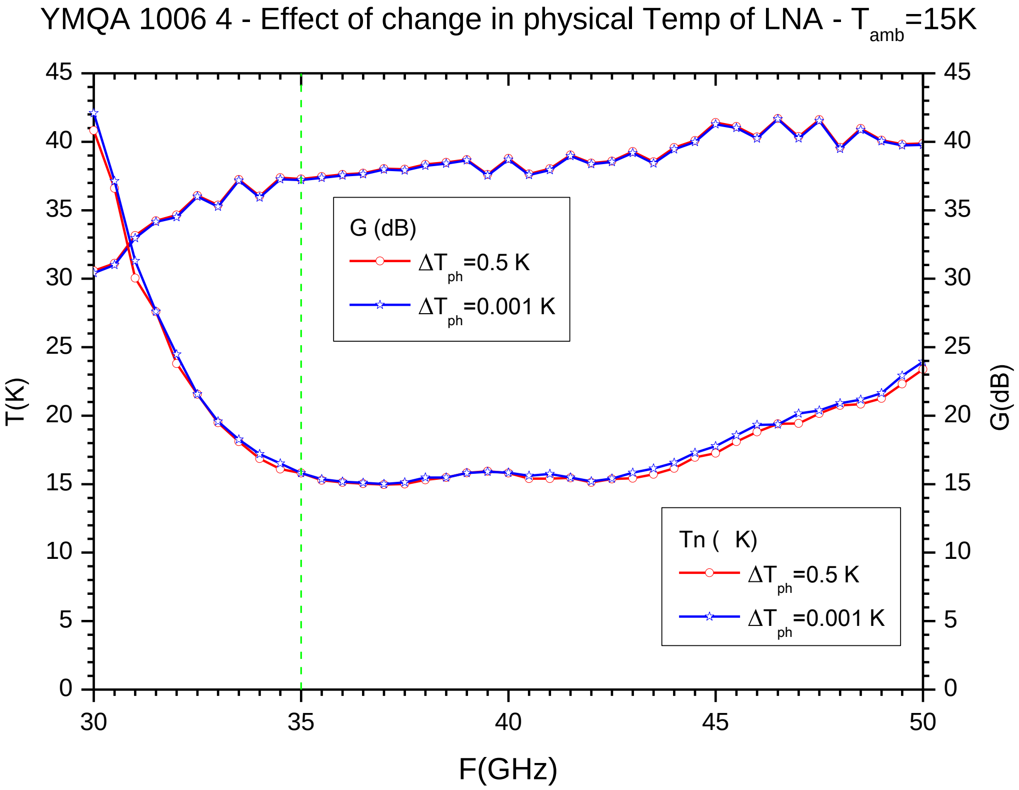

Figure 10. Effect of change of the physical temperature of the amplifier between hot and cold states of the heated load in the measurement of noise temperature. As this plot shows a change of ΔT_{ph}=0.5K does not degrade significantly the accuracy of the measurement in this case.

6. Conclusions.

A waveguide heated load has been developed to be used as an alternative to the ambient/LN2 absorber method used for measuring the noise temperature of cryogenic amplifiers in Q band. This method is potentially more accurate since it avoids the uncertainties related with the use of additional horns, vacuum windows and the accuracy of the temperature of porous absorbers soaked in LN2. Besides, the impedance presented in the hot and cold states is almost constant, drastically reducing the ripples often found in the noise measurement of highly reflective devices.

The accuracy of the noise measurements with the heated load could be limited by:

- The uncertainty in the physical temperature of the microwave absorber (the absorber is a poor thermal conductor and its physical temperature could be slightly different than the temperature sensed in the outer surface of the metal housing).
- The uncertainty in the contribution of the loss of the SS waveguide to the effective output noise temperature (the dependence of the loss with temperature and the temperature distribution along the waveguide are not perfectly known).
- The residual change of the reflection coefficient with the temperature (although this is expected to be negligible).
- The effect of heating the amplifier with the power dissipated by the heating of the load in the hot state.
- The limited speed: The heated load is slow compared with diode noise sources. Care should be taken with errors due to a possible gain drift of the receiver and the amplifier during the measurement.

The measurements presented in this report demonstrate that the method can be practically implemented and that the limitations factors cited above do not severely impact the accuracy of the measurements.

From the comparison with previous noise measurements with ambient/LN2 absorbers it appears that the results of the measured noise temperature of a typical Q band cryogenic amplifier are **~1.9 K lower** than with the previous method. This includes the theoretical correction due to loss in the SS waveguide. The heated load method is believed to be more accurate than the ambient/LN2 method.

7. Future work

The uncertainty introduced by the loss of the SS waveguide could be reduced by lowering the electrical loss. This could be achieved by electroplating the inner walls of the waveguide with a thin layer (~1µm) of gold or copper. This will not degrade the thermal isolation significantly.

The cooling speed can be improved by reducing the heat capacity of the load. This will require a totally different mechanical design.

8. References.

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