Heated Cryogenic Load in W band (70-110 GHz) Waveguide for Precision Noise Measurements

I. Malo, J.D. Gallego, M. Diez, I. López, R. Amils, A. García, R. García, G. Martínez.

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Observatorio de Yebes
Apartado 148
19080 Guadalajara
SPAIN
Phone: +34 949 29 03 11

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1. Introduction.

A heated load is an option to implement the hot/cold load method for the noise measurements, that improves accuracy, reduces the ripple of the measurements and eliminates the need of liquid nitrogen. This report presents a design of a heated load for W band based on the improved heated load designed for the Q band and presented in the Technical Report CDT 2016-6 [1].

2. Fabrication of the heated load.

The heated load is built with a piece of regular rectangular WR-10 copper (Cu) waveguide with the absorber inside (see Figure 1). The stainless steel waveguide is directly soldered[1] to the copper waveguide.

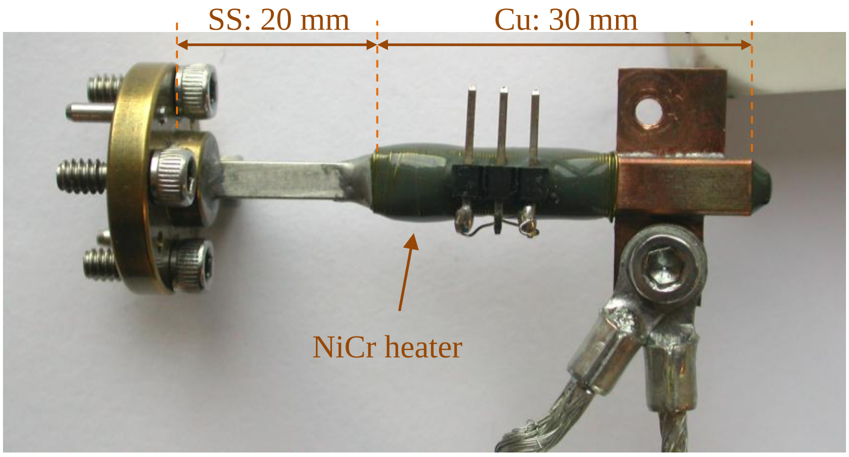

Figure 1. W band heated load made of a 30 mm long piece of WR-10 Cu waveguide soldered to a 20 mm long piece of SS 304 waveguide.

The absorber[2] is machined with a wedge shape, tapered in two directions from a rectangular bar. It 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 [2] 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 25.4 mm is required for the WR10 waveguide dimensions (2.54 x 1.27 mm). The absorber piece is inserted into the Cu waveguide through the open end. Probably only part of the piece of absorber is perfectly glued to the waveguide walls since the epoxy[3], initially deposited in two of the sides of the absorber, is dragged when the piece is inserted. Due to this, the thermal contact between the absorber and the waveguide could not be good.

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[1] *SnPb alloy: SN60; fusion temperature: 190 ºC.*

[2] *The material of the absorber is the ECCOSORB MF-117, used in band Q heated loads (T.R. CDT 2016-3/6).*

[3] *Epoxy Scotch-Weld EC2216.*

The 50 Ω heater is made of a nichrome wire[4] coiled around the Cu waveguide and covered with epoxy[5] for protection. The temperature sensor is attached to the Cu waveguide by means of a small copper plate[6] soldered[1] to the waveguide. Besides, attached to this copper plate, there are two braids connecting the heated load to the cold plate of the cryostat.

3. Thermal performance.

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 setup for the heated load thermal test is shown in Figure 2. The NiCr heater is connected to the 336 Temperature Controller (output 1, see configuration in Table 1). The PID parameters are estimated by the “Autotuning” function of the 336 Temperature Controller when the physical temperature of the load is 20 K[7]. The base plate of the cryostat is stabilized to 15 K by an independent loop (output 2 of the 336 Temperature Controller).

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	Closed loop PID
Ramp	40 K/min

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[4] *NiCr wire, AWG 32, Lakeshore WNC-32-250. For 50 Ω a length of 1.50 m is needed.*

[5] E*poxy Scotch-Weld EC2216*

[6] *Cu 1 mm thick.*

[7] *It would be better to estimate the PID parameters at 40 K instead of at 20 K.*

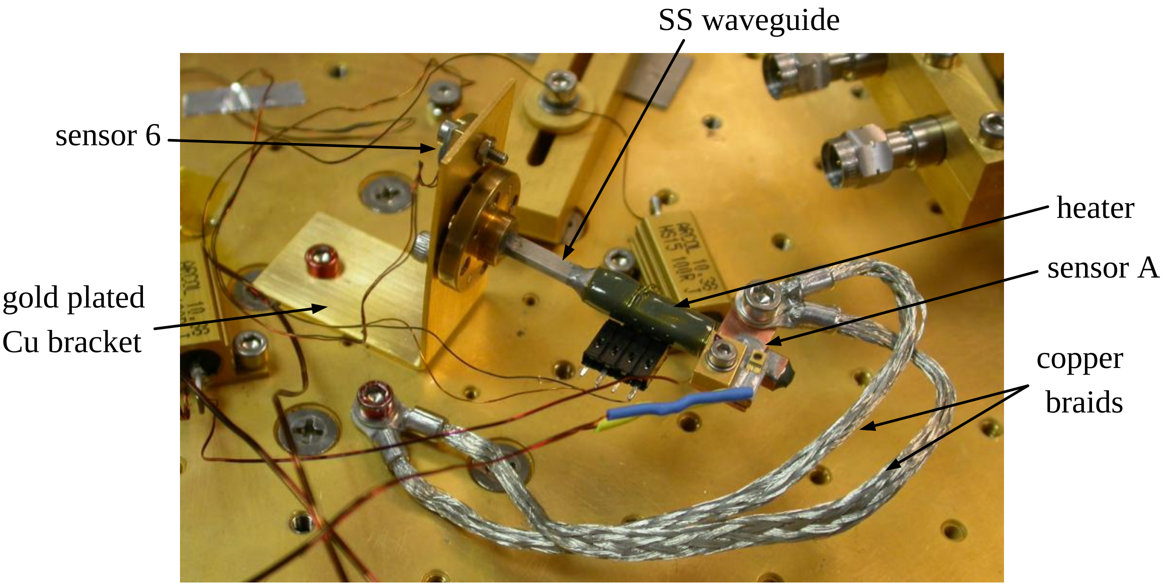

Figure 2. Setup for the heated load thermal test.

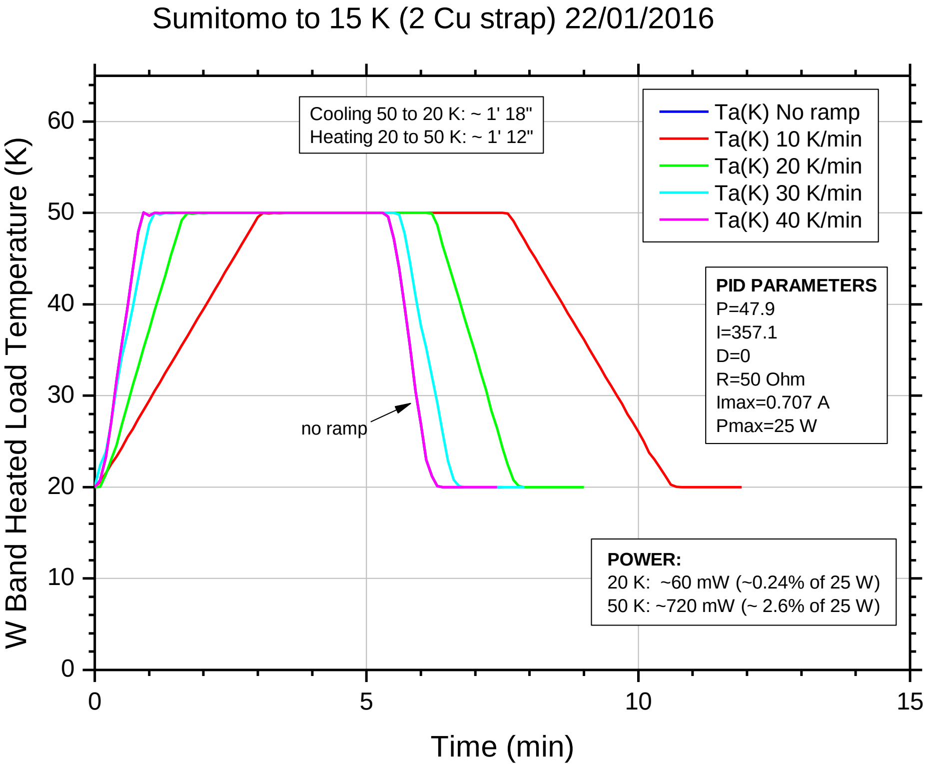

Figure 3. Thermal response of the heated load in W band with two identical braids. The PID parameters where estimated when the physical temperature of the load is 20 K. A ramp of 40 K/min is the best option to minimize the heating time.

An accurate noise measurement requires that the entire absorber reaches a set temperature. But the temperature of the absorber cannot be sensed; only the temperature of the sensor attached to the heated load is known. The absorber and sensor temperatures could be different because they are not in contact. In order to obtain a relation between them, a comparative measurement of the sensor temperature and of the power received from the heated load is presented in Figures 4-5. The conclusion of this measurement is that, in the heating cycle of the heated load, the absorber takes 5 minutes to warm up since the temperature of the sensor start to increase from 20 K; in the cooling cycle, the absorber takes only 3 minutes to cool down since the temperature of the sensor start to decrease from 50 K.

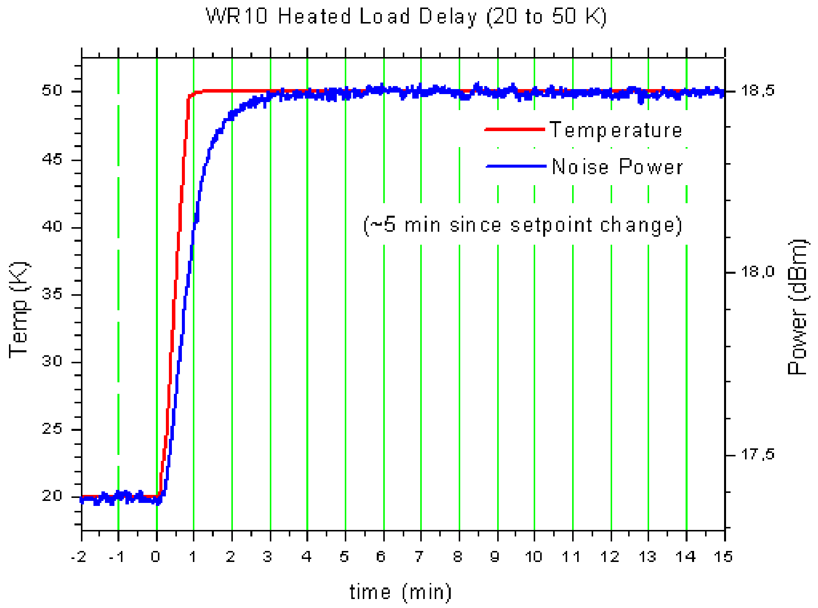

Figure 4. Comparative measurement of the sensor temperature and of the power received from the heated load, in the heating cycle from 20 to 50 K. The absorber takes 5 minutes to warm up.

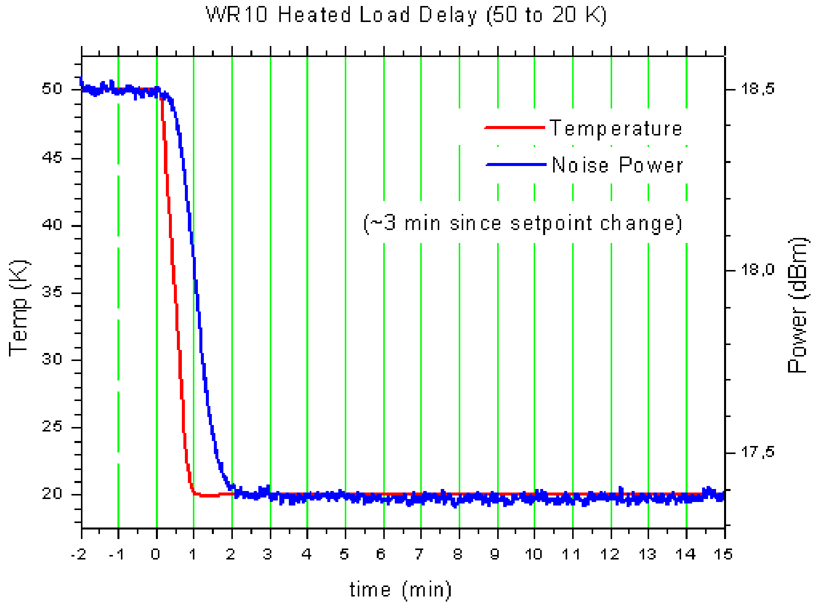

Figure 5. Comparative measurement of the sensor temperature and of the power received from the heated load, in the cooling cycle from 50 to 20 K. The absorber takes 3 minutes to cool down.

4. Input reflection.

Excellent results are obtained for the input reflection of the heated load. At ambient temperature, return loss is better than -28 dB, as we can see in Figure 6 compared with the Keysight calibration load and a Quinstar[8] waveguide termination. 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.

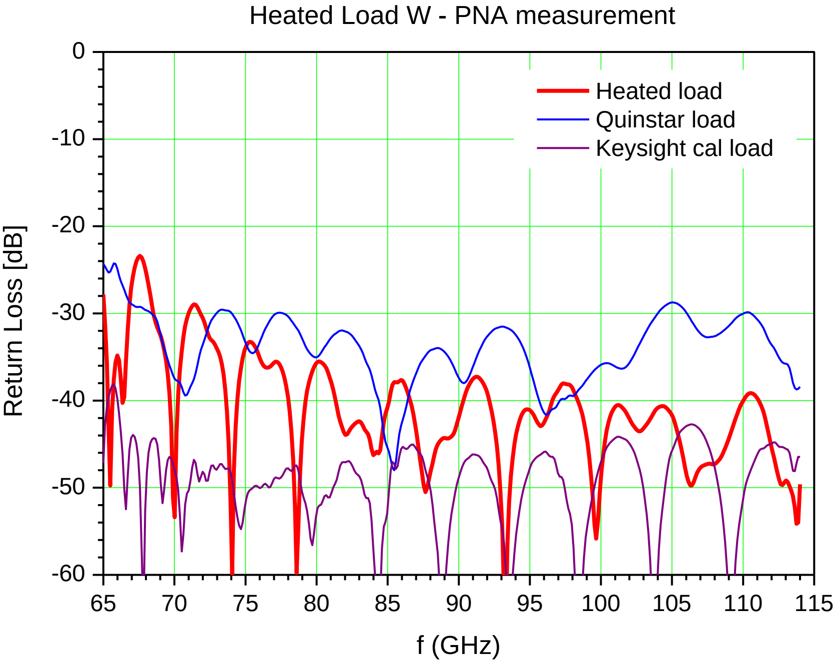

Figure 6. Return loss of the heated load in W band compared to a Quinstar waveguide termination[8] and the Keysight calibration load.

5. Noise measurements.

The heated load was validated by performing cryogenic noise measurements of a W band amplifier LNF 016Z[9] (Figure 7). The temperature of the LNA is stabilized to 15 K by an independent loop (output 2) and the temperature sensor, called “C”, is attached to the LNA. The heated load configuration used is described in Figure 3. The hot and cold set points were 50 and 20 K respectively.

Correction of the effective heat load temperature

The effect of the losses of the stainless steel waveguide between the amplifier and the heated load has been estimated using the method presented in [3]. The theoretical looses for a 20 mm

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[8] *Serial number QWN-W R 000*

[9] *Test performed on LNF 016Z, a 75-110 GHz MMIC amplifier. Cryogenic bias used: (Vd Id Vg) = (1.05 V 20 mA 1.69 V).*

long SS waveguide, at 110 GHz, with a conductivity of $1.391 \cdot 10^{6}\ \Omega^{-1}\ \mathrm{m}^{-1}$ for the SS304 at 300 K [4], are 0.254 dB. Assuming a non-linear physical temperature distribution in the SS waveguide, for the boundary conditions of 15 and 50 K of temperature respectively on each side, the calculated mean effective noise temperature presented at the input of the amplifier at 110 GHz is **49.2 K** (a reduction of **0.8 K** respect to the physical temperature). Note that if the correction is not applied, the noise temperature result will be systematically overestimated. In the same way, for the boundary conditions of 15 and 20 K, the reduction is lower than 0.1 K and it will be not taken into account.

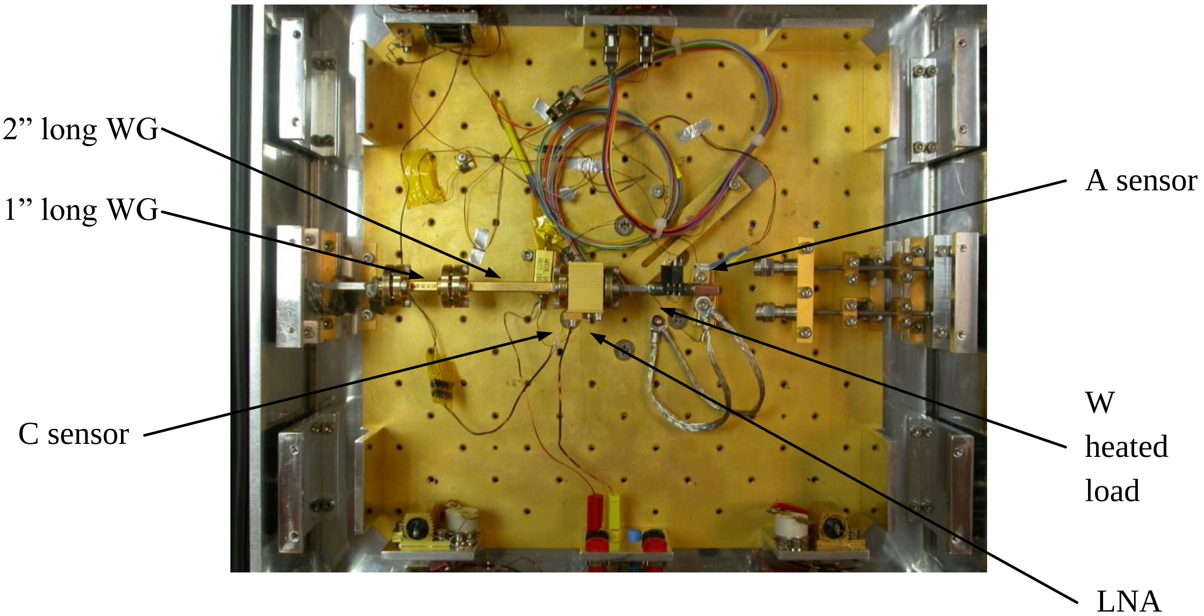

Figure 7. Measurement of the LNF 016Z with the W heated load.

Comparison with LN2 measurements

The noise measurement of the LNF 016Z amplifier is compared with the classical ambient / LN2 absorbers measurement (Figure 8).

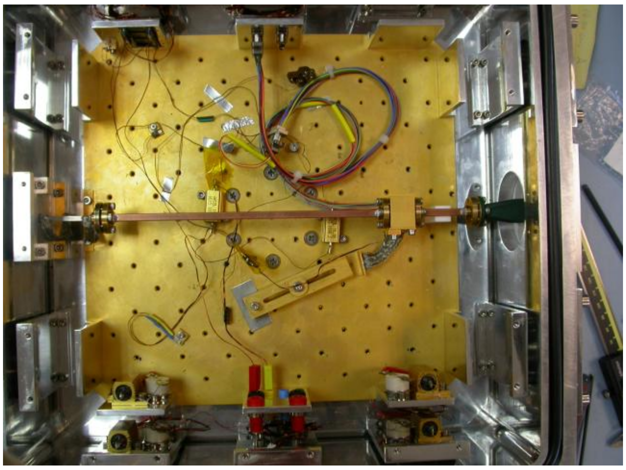

Figure 8. Measurement of the LNF 016Z with LN2. At the input of the amplifier there are a Cu waveguide 40 mm long, a horn, a IR filter, a Mylar window 70 µm thick and an expanded polystyrene piece 50 mm thick.

Table 2 and Figure 9 present the results of the comparison. The agreement between the measurements is very good.

Measurement	*T mean (70-110 GHz)*
Horn: Ambient/ LN2 loads	89.26 K
Waveguide Heated load	88.68 K

Table 2. Comparison of the average noise temperature obtained in the 70-110 GHz band with ambient/LN2 absorbers and with the heated load.

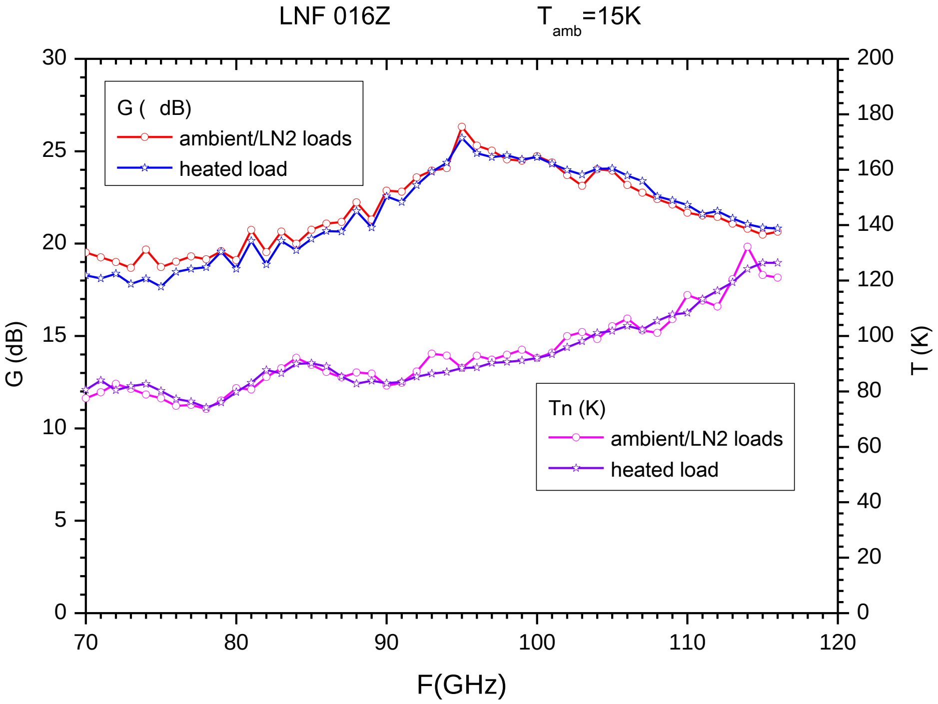

Figure 9. Comparison of the measurements of gain and noise temperature of the LNF 016Z amplifier using the heated load (blue line) against the measurement using ambient/LN2 absorbers (red line).

Note that in the LN2 measurements there are an IR filter, a 70 µm thick of Mylar window, a horn[10] and a Cu waveguide 40 mm long at the input of the amplifier which losses increase the noise temperature measured. At 15 K and 90 GHz, the theoretical losses of the Cu waveguide are 0.038 dB (for the Cu conductivity of $4.7 \cdot 10^8$ S/m) so the mean temperature of the amplifier is around 0.9 K lower than the temperature measured (T_{LN2} corrected = 88.36 K).

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[10] A piramidal horn with serial number 27240-20 from Flann.

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 W band. This method is potentially more accurate since it avoids the uncertainties related with the use of additional horns, waveguides, 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, reducing the ripples often found in the noise measurement of highly reflective devices.

In order to improve the accuracy of the noise measurements with the heated load, the hot temperature value used must be the mean effective output noise temperature of the load (i.e. the hot physical temperature corrected by the effect of the loss in the stainless steel waveguide). For boundary conditions of 15 and 50 K of temperature respectively on each side of the SS waveguide of our load, the calculated mean effective output noise temperature presented at the input of the amplifier is **49.2 K.** This correction could be significant, especially in the case of extremely low noise amplifiers.

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.

References.

1. Malo, I.; Gallego, J.D.; Amils, R.; Diez, M.; López, I.; García, R.; Barcia, A.; “Heated Cryogenic Load in Q band (33-50 GHz) Waveguide for Precision Noise Measurements”, in Yebes Observatory IT-CDT-2016-3.

2. *http://www.eccosorb.com/Collateral/Documents/English-US/MF.pdf.*

3. Gallego, J.D.; Malo, I.; López, I.; Diez, M.; "Thermal Conductivity and Electrical Loss of Thin Wall Millimeter Wave Stainless Steel Waveguides", in Yebes Observatory IT-CDT-2015-14.

4. C. Y. Ho; T. K. Chu, “Electrical resistivity and thermal conductivity of nine selected AISI stainless steels,” pp. 16-17, CINIAS Report 45, Purdue University, September 1977.