Effect of the direct detection effect on the HEB receiver sensitivity calibration

S. Cherednichenko, V. Drakinskiy, T. Berg, E. Kollberg, I.Angelov.

***Abstract*—We analyze the scale of the HEB receiver sensitivity calibration error caused by the so called "direct detection effect". The effect comes from changing of the HEB parameters when whey face the calibration loads of different temperatures. We found that for HIFI Band 6 mixers (Herschel Space Observatory) the noise temperature error is of the order of 8% for 300K/77K loads (lab receiver) and 2.5% for 100K/10K loads (in HIFI). Using different approach we also predict that with an isolator between the mixer and the low noise amplifiers the error can be much smaller.**

***Index Terms*—HEB, mixer, terahertz, noise temperature.**

I. INTRODUCTION

1.4-1.7 THz and 1.6-1.9 THz NbN Hot-Electron Bolometer (HEB) mixers [1] are intended for Band 6 of the HIFI instrument of the Herschel Space Observatory [2]. A number of other radioastronomical projects, such as APEX, TELIS, SOFIA, involve the same HEB mixers [3]. One of the crucial requirements is the calibration accuracy of the receiver noise temperature which for HIFI is of the order of 1 %. Noise temperature calibration will be done using 10 K and 100 K "cold"-"hot" loads placed in the receiver beam way after the dual-way diplexer (the telescope signal is split for two mixers of different polarization). The calibration loads are broadband black body sources. The radiation is coupled to the HEB mixers via relatively broadband planar double- slot antennas. The overall single –mode hot-cold signal power, incident on the mixer, is estimated from the Planck law as 3 nW, i.e. not negligible comparing to the LO power incident on the mixers (200÷300 nW). The electron temperature of the HEB is proportional to the absorbed RF+LO power. An IF signal is generated by the electron temperature oscillations caused by the mixing of the LO and the RF waves. Therefore, for different RF input powers (for the hot and the cold loads) the HEB mixer is at different electron temperatures and hence has different gain and noise. Depending on the HEB volume, the critical current, the RF bandwidth of the antenna, the change of the mixer electron temperature is seen on the mixer bias current (in case of the voltage bias). The shift of the HEB's bias current is traditionally called "a direct detection effect" since it is just this current modulation which is used for the response read-out of all bolometric direct detectors. Although, the linearity of HEB mixers' response to hot-cold load has been verified up to 1000 K for the smallest NbN HEBs (a number of papers have been published), the direct detection effect modifies the Y-factor and introduces a systematic error in the receiver noise temperature calibration. In this paper we discuss different techniques to calibrate out the direct detection effect.

Manuscript received May 30, 2005. This work was supported the Swedish National Space Board.

Authors are with the Microwave Electronic Laboratory, MC2, Chalmers University of Technology, SE-412 96, Gothenburg, Sweden, (corresponding author S.Cherednichenko, e-mail: serguei.cherednichenko@ mc2.chalmers. se).

II. DIRECT DETECTION EFFECT

A. *The noise temperature error*

A typical HEB receiver DSB noise temperature at 1.63 THz is shown in Figure 1 on an example of the Band 6 Low mixer of the HIFI instrument of the Herschel Space Observatory. We build up the discussion in this paper based on the results obtained for this mixer, which is similar to the Flight Mixer to be installed in HIFI.

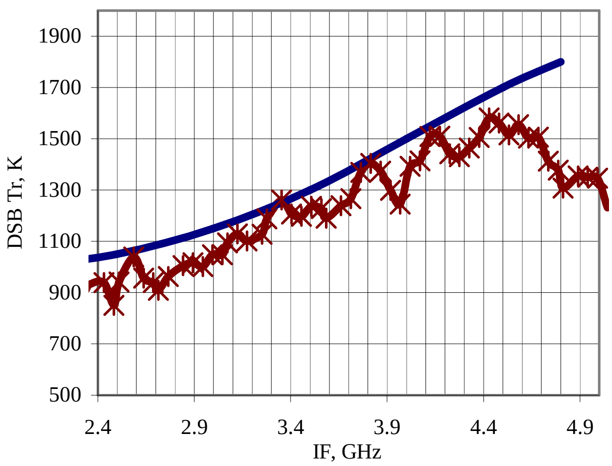

Figure 1.HIFI Band 6 Low HEB receiver noise temperature at 1.63 THz LO frequency, corrected for the input optics loss.

The receiver sensitivity is measured with the Y-factor technique. Y-factor, corresponding to the noise temperature of 1000 K is about 0.8 dB (see Figure 2). In order to obtain a certain noise temperature measurements accuracy the Y-factor error shall not exceed the corresponding value. In Figure 3 we calculate the Y-factor error as a function of Tr which leads to

1%, 5%, and 10% of the noise temperature error. From this figure we can see that the Y-factor shall be measured with the accuracy better than 0.01dB in order to achieve the Tr error as low as 1% at 1000 K level. It relaxes to 0.035dB for the Tr error of 5%.

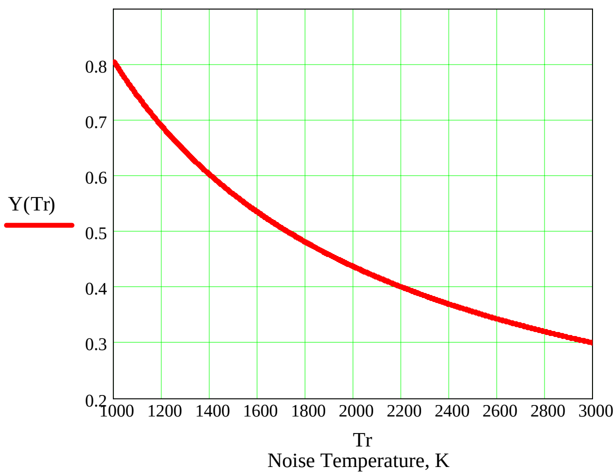

Figure 2. Y-factor versus noise temperature.

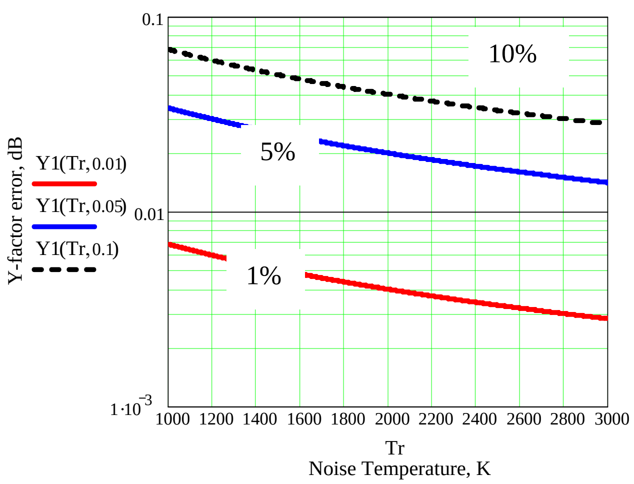

Figure 3. Y-factor error corresponding to the 1%, 5% and 10% of the noise temperature error as a function of the receiver noise temperature.

B. *RF power coupling to the mixer*

Single mode black body power coupled to the HEB mixer is defined by the antenna RF bandwidth. In our investigation, a 1.6THz double slot antenna was used of the same type as for the HIFI Band 6 Low mixers. The antenna is used in its low impedance resonance in order to facilitate an efficient matching to an HEB mixer which normal state impedance (resistance) is of the order of 50÷100 Ohm. Low impedance resonance for DSAs is much more broad comparing to the high impedance resonance (it is opposite as for the double dipole antennas) and reaches relative bandwidth of about 30% [4]. Its RF band was measured by a Fourier Transform Spectrometer (FTS) with the HEB as a direct detector (see Figure 4, solid line) (see also [5]). The obtained curve was approximated with a function I(f), and the coupled black body power was calculated as

$$P(T) = \int_{0.5}^{3} \varepsilon(f,T) \cdot I(f) \cdot df \;,$$

where

$$\varepsilon(f,T) = hf \frac{1}{\exp\left[\dfrac{hf}{kT}\right] - 1}$$

is the single mode black body power spectral density.

In the band of the discussed antenna and at assumed optical losses [6] the 300 K (77 K) load produces about 2.8 nW (1.6 nW) referenced to the silicon lens input.

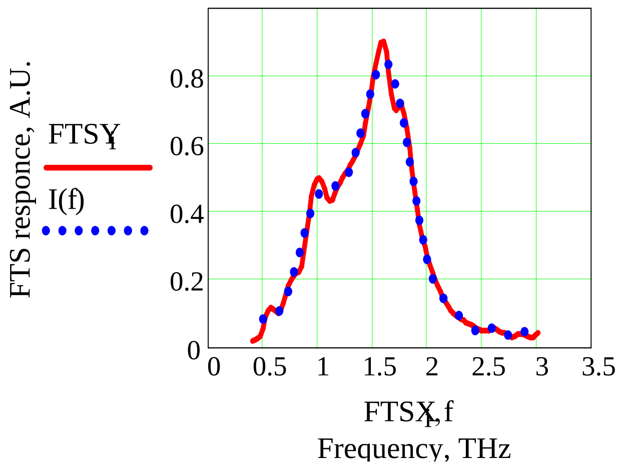

Figure 4. 1.6THz double slot antenna RF band (solid) and an approximation curve (dots).

The LO power referred to the Si lens is of the order of 100-200 nW for the discussed HEB mixers at 4.2 K bath temperature. Such large uncertainty of the required LO power is caused by the difficulty to measure 1.6THz beam power at such low power levels. Even when a thin beam splitter is used with reflectivity of a few percent, the transmitted power is only of the order of 10÷20 µW. The LO power increases the electron temperature from the bath temperature (4.2 K) up to Tc (9 K). A set of the IV-curves corresponding to different LO power values incident on the mixer is shown in Figure 5. The LO power tuning range is about 3dB from the highest IV to the lowest IV shown in the figure. Equivalently, the change from the cold (77 K) load to the hot (290 K) load changes the IV curve as shown in Figure 6. The higher input load corresponds to the higher dc resistance, i.e. lower current at the constant voltage biasing regime.

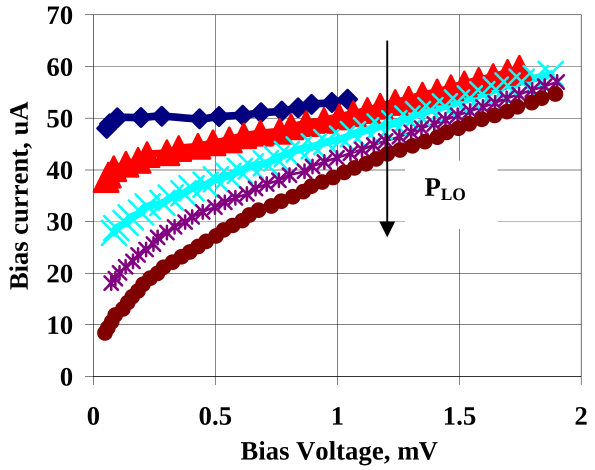

Figure 5. Current – voltage curves under different LO power levels (mixer faces the hot load).

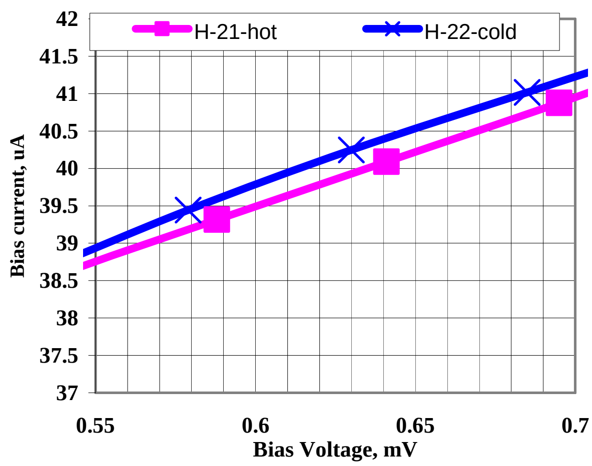

Figure 6. Current –voltage curves under the hot (lower) and the cold(higher) loads. The shown bias area corresponds to the minimum mixer noise temperature.

The mixer output power, P_{if}, consists of the down converted (from RF to IF) input signal and the mixer output noise: $P_{if}=P_{load}\ G + T_{out}$. The output power corresponding to the IV curves from Figure 5 is shown in Figure 7. As P_{load} changes from 300K to 77K , the IF output change is:

$$dP_{if} = dP_{load}\ G - P77\ dG - dT_{out}, \qquad (1)$$

dG and dT_{out} is caused by the change of bias current dI (see Figure 6), and for an ideal HEB mixer (no direct detection effect) both dG and dT_{out} shall be zero.

If dI=0, then both dG=0 and dT_{out}=0. In this case dP_{if} is caused by the heterodyne response, i.e. dP_{load} G . If dI>0, then dG>0 and dT_{out}>0.

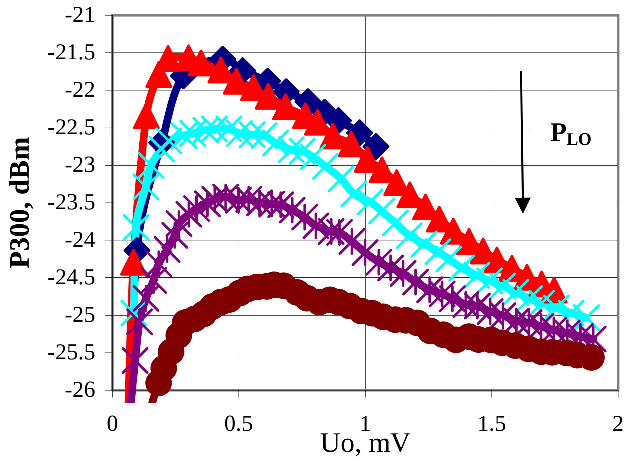

Figure 7. Receiver output power vs bias voltage at different LO power levels. The mixer is loaded on 290 K input load.

In this case, dP_{if} is reduced, hence the Y-factor. The impact of the direct detection effect on the Y-factor measurements depends on the bias current shift (dI), and how strong the G(I) and Tout(I) functions are. For the discussed mixer dI=0.25 µA at the bias point corresponding to the lowest mixer noise temperature (shown in Figure 6).

It has been suggested to define the Tout(I) dependence from Figure 7 assuming that the mixer gain does not change with the current (for small dI values), i.e. dG=0. The obtained correction factor for $dT_{out} = \frac{\partial P_{300}}{\partial I} dI$ was applied to the Equation 1 and the corrected Y-factor was obtained. This method was qualitatively used to analyze the direct detection effect scale by many authors and quantitatively was also applied in [7]. But in this case an uncertainty remains that the mixer gain G shall be LO power dependent, and by changing the LO power the gain changes as well. Especially, this method is valid if the mixer gain is assumed to be bias current independent, which is not quite obvious.

We would like to verify this technique and discuss alternative methods to take into account the direct detection effect.

III. EXPERIMENT-I

We investigated two methods to compensate the HEB electron temperature shift at different input loads: by a resistive heater and by an RF heater. In both cases the LO frequency was 1.63 THz.

As a resistive heater we used a high power resistor mounted on the mixer unit. The mixer bias voltage was 0.6mV. In this case the LO power was constant and the mixer bath temperature was changed.

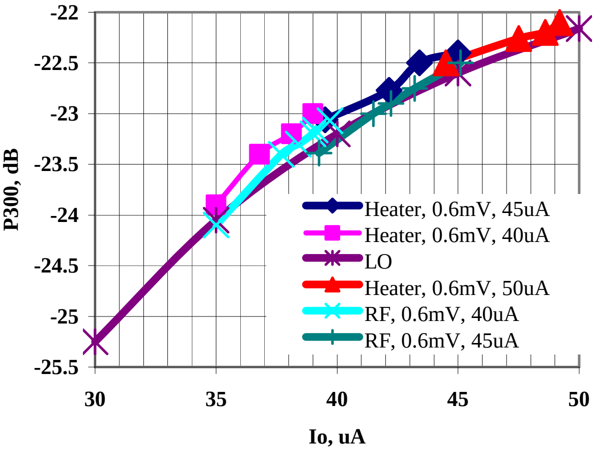

Figure 8. Receiver output power vs bias current at a fixed bias voltage. The bias current was changed by changing the mixer bath temperature.

The applied heating was not very strong and it caused the bias current reduction at maximum by 5 µm at around each used bias current. The measurement were carried out at LO power levels corresponding to the IVs from Figure 5.

The RF heating was applied from a 600 GHz backwards wave oscillator. The BWO beam was inserted into the LO beam path with a second beam splitter. The RF heating occurs via the photon absorption by the electrons with the consequent heat removal by the phonons, i.e. in the heat balance equation the input power changes. While with the resistive heater the bath temperature changes (the border conditions of the heat balance equation). Since these two processes are not identical both heating mechanisms have to be investigated.

For comparison we have also measured P_{if} vs bias current when tuned with the LO power (at the constant bath temperature and the input load). This is shown in Figure 8 with a long solid line. The data obtained for the constant LO power (tuned by the heater and the BWO) are shown with the filled diamonds and the crosses, correspondingly.

For the first approximation, for all three bias current tuning (LO, heater, and BWO) the $P_{if}(I)$ curves coincide with each other. This might be indicating that the method of [7] could be correct. $\delta P_{300}/\delta I$ is about 0.2dB/µA. Since dI, caused by the direct detection is of the order of 0.2 µA, then dT_{out}=0.04dB. The receiver noise temperature (including input optical losses) is 1700 K, and from Figure 3 we see that 0.04dB Y-factor error corresponds to about 8% of the noise temperature error.

We see that dI= 0.2 µA is caused by the 2.8 nW - 1.6 nW= 1.2 nW signal from 300K/77K calibration loads. HIFI calibration loads have bath temperatures of 100 K and 10 K. Since in HIFI the optical loss from the loads to the mixer lens is very low, the mixer will face 0.74 nW input signal change referenced to the silicon lens input. This is a factor of 2 lower than for the lab receiver. Therefore, it will cause 0.02 dB Y-factor error. Since in this case we refer the Y-factor to the silicon lens (not to the calibration loads like for the lab receiver, through the lossy air, the vacuum window and the IR filters), then the receiver noise temperature is about 1000 K (calibrated for the lab receiver input losses). From Figure 3 we obtain that for this noise level 0.02dB Y-factor error corresponds to 2.5% noise temperature error.

IV. Experiment-II

When no direct detection is present the IF signal change when 300K load is replaced with 77 K load is caused by the heterodyne response and log(P300)-log(P77) is positive (we monitor the IF signal in logarithmic scale, i.e. in dBm). While, as it is seen from Figure 7 the $P_{if}(I)$ and G(I) have a positive gradient, at least at the bias area with the maximum HEB sensitivity. Therefore, the direct detection effect reduces the Y-factor. Of course, during the astronomical observations the input signal power will be much less than the calibration loads power. However, it is important to understand the scale of the direct detection effect influence on the HEB calibration for more accurate power measurements of the astronomical sources.

A possible solution would be to eliminate the heterodyne response and look at the log(P300)-log(P77) caused by the bias point shift only. From Figure 4 once can see that at 2.6 THz the double slot antenna response drops nearly to zero. The FIR laser, which we used as the LO source, has a 2.6THz line with the output power of a few mW. We could pump our mixer at this frequency with the same 3 µm Milar beam splitter as for the 1.6 THz experiment. The HEB IV curves for these two LO frequencies are absolutely identical as it seen from Figure 9.

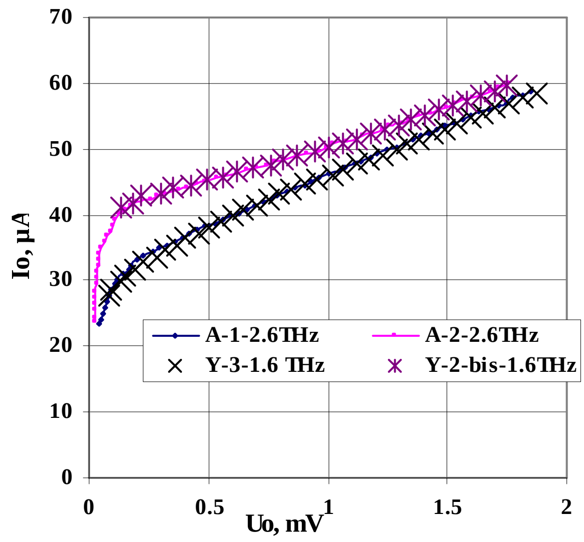

Figure 9. HEB IV-curves pumped to the optimal state with the 1.6 THz LO (crosses) and with the 2.6 THz LO (solid) (IVs with two different LO powers are shown).

This is because both frequencies are much above the energy gap frequency of the used thin NbN superconducting film (T_c≈9 K). However, the direct detection effect scale is defined by the calibration loads power coupled to the mixer. This remained unchanged since it is the same mixer-antenna which is used. The observed dI change for 2.6 THz was the same as for 1.6 THz as the loads switched from 300 K to 77 K.

As we have mentioned, for 2.6 THz LO frequency with the 1.6 THz DSA HEB mixer, the mixer gain shall be nearly zero due to the drop of the antenna efficiency. From Eq.1 we shall see that dP_{if} is caused by the direct detection effect only and the measured Y-factor log(P300)-log(P77) shall be negative (or zero if no direct detection effect is present). Surprisingly we observed a positive Y-factor of the order of 0.05÷0.1 dB (for different samples). Since in Chapter III we have estimated the direct detection effect on the Y-factor as -0.04 dB, it results in the real Y-factor (measured Y-factor plus direct detection calibration) of the order of 0.1-0.15dB at 2.6 THz, which seems to be too high for such low antenna efficiency as shown in Figure 4.

We shall note that Band 6 mixers of HIFI instrument will operate without IF isolators between the mixers and the LNAs. The reason is unavailability of cryogenic isolators for the 2.4-4.8 GHz band. In our measurements we used an Alcatel HIFI prototype LNA without an isolator as well. Therefore, the LNA input is directly loaded with the HEB mixer which IF impedance changes in a wide range through the discussed IF band [8]. An important HEB parameter defining the HEB IF impedance is the mixer dV/dI at the operation point. As for the IVs from Figure 9 the dV/dI changes with the bias point. It causes the HEB impedance to change. A model of a InP HEM amplifier (Chalmers design) was used in order to estimate how sensitive the LNA gain is to the input load impedance. Preliminary calculations show that the LNA gain increases by 0.6 dB when the input load impedance increases from 50 Ohm to 60 Ohm. Of course, the impedance change associated with the direct detection effect is not more than 1 Ohm, however our modeling was quite simplified as well. It shall also mean that the direct detection error introduced into the Y-factor shall be intermediate frequency dependent.

In order to check the discussed phenomenon we introduced a 4-8 GHz isolator between the HEB and the LNA. The LNA band was 2.4-4.8 GHz, hence the LNA-isolator common band was 4-4.8 GHz. We compared the experiment at 2.6 THz, discussed in this chapter, with such isolator and without it. Intermediate frequency was 4 GHz in both cases. We observed a positive Y-factor of 0.05dB without the isolator, and no distinguished Y-factor with the isolator. The set of curves as in Figure 7 has to be recorded for the LNA with the isolator and $P_{300}(I)$ shall be compared for the case without the isolator. This is planned for the future.

V. Conclusion.

Direct detection effect is defined as the shift of the HEB bias current when the 300 K calibration load is switched to 77 K load. The shift is caused by the heating of the HEB by the black body power absorbed by the HEB via the double slot antenna. The bias current shift introduces an error into the Y-factor measurements. Different techniques can be used in order to figure out the scale of the effect from the measured dI value. Using a simplified method we obtain that this effect gives about 8% noise temperature error for the Band 6 Low mixers of the HIFI instrument (Herschel Space Observatory). For these mixers an error of 2.5 % is expected when the calibration loads with 100 K and 10 K (as in HIFI) are used (assuming no coupling loss from the loads to the mixer).

A clear evidence of the bias current shift effect on the HEB-LNA matching has been observed when comparing the results with and without the IF isolator. A more thorough investigation is needed in order to understand the scale of the effect quantitatively. An isolator, covering the entire IF band (2.4-4.8 GHz), might be an option in order to minimize the Y-factor error.

Acknowledgements.

For the HEB mixers we used NbN films deposited at Moscow State Pedagogical University (Russia). The work was supported by Swedish National Space Board in the frame of the HEB Mixers for Herschel Space Observatory project.

References:

[1] E. M. Gershenzon, G. N. Gol'tsman, I. G. Gogidze, A. I. Elant'ev, B. S. Karasik and A. D. Semenov, "Millimeter and submillimeter range mixer based on electronic heating of superconducting films in the resistive state", Sov. Phys. Superconductivity, 3, 1582, 1990

[2] http://sci.esa.int/sciencee/www/object/index.cfm?fobjectid=34682

[3] U.Mair et al in this Prceedings; and D.Meledin at al in this Proceedings.

[4] M. Kominami, D. M. Pozar, and D. H. Schaubert, "Dipole and slot elements and arrays on semi-infinite substrates," IEEE *Trans. Antennas Propagal.* vol. 33, pp. 600-607, June 1985.

[5] D. Loudkov, P. Khosropanah, S. Cherednichenko, A. Adam, H. Merkel, E. Kollberg, G. Gol'tsman, "Broadband Fourier Transform Spectrometer (FTS) measurements of spiral and double- slot planar antennas at THz frequencies", *Proc. 13th*. International Symposium on Space Terahertz Technology, *Cambridge, MA , March 2002*

[6] Air loss: 0.6dB, vacuum window 0.7dB, IR filter (at 77K) 0.3dB, IR filter (at 10K) 0.3dB.

[7] Baselmans, J.J.A.; Hajenius, M.; Gao, J.R.; Baryshev, A.; Kooi, J.; Klapwijk, T.M.; Voronov, B.; de Korte, P.; Gol'tsman, G.;" NbN hot electron bolometer mixers: sensitivity, LO power, direct detection and stability", IEEE Trans.Appli. Supercond., IVolume 15, Issue 2, Part 1, June 2005 Page(s):484 - 489

[8] H.Ekström, B.Karasik, E.Kollberg, and K.S.Yngvesson, "Conversion gain and noise of niobium superconducting hot-electron –mixers", IEEE Trans., MTT, vol 43, n.4, 1995.