A BROADBAND TERAHERTZ HETERODYNE RECEIVER WITH AN NbN HEB MIXER.

S. Cherednichenko, M. Kroug *, P. Khosropanah, A. Adam, H. Merkel, E. Kollberg

Department of Microwave Electronics, Chalmers University of Technology, Gothenburg, S-412 96, Sweden

D. Loudkov, B. Voronov, G. Gol'tsman

Department of Physics, Moscow State Pedagogical University, Moscow, 119435, Russia

H. Richter, H.-W. Hübers.

Institute for Space Sensor Technology DLR, Berlin, Germany

* Delft University of Technology, DIMES, Delft, The Netherlands

We present a broadband and low noise heterodyne receiver for 1.4-1.7 THz designed for the Hershel Space Observatory. A phonon- cooled NbN HEB mixer was integrated with a normal metal double- slot antenna and an elliptical silicon lens. DSB receiver noise temperature Tr was measured from 1 GHz through 8GHz intermediate frequency band with 50 MHz instantaneous bandwidth. At 4.2 K bath temperature and at 1.6 THz LO frequency Tr is 800 K with the receiver noise bandwidth of 5 GHz. While at 2 K bath temperature Tr was as low as 700 K. At 0.6 THz and 1.1 THz a spiral antenna integrated NbN HEB mixer showed the receiver noise temperature 500 K and 800 K, though no antireflection coating was used in this case. Tr of 1100 K was achieved at 2.5 THz while the receiver noise bandwidth was 4 GHz.

1. Introduction

Extension of radio astronomical observations above 1 THz has happened during the last years. It was motivated by the big progress in the areas of both mixers and local oscillators. A number of ground based, such as TREND (1.5 THz, South Pole), air- and space born (SOFIA, Herschel) observatories are now under construction. For these applications the main orientation is made on hot electron bolometer (HEB) mixers [1, 2]. An operation of these types of mixers up to 5 THz was experimentally shown in references [3]. Both quasi- optically, QO, (planar antenna integrated) and wave- guide, WG, (feed horn with a fixed tuned or tunable mixer block) coupled receivers designs were used by different groups [4]. Due to the relative technological simplicity of the lithographical fabrication technique, QO HEB receivers have been quoted much more often in the literature. However, certain advantages are associated with WG type of receivers. The radiation mode purity and probably (however, no experimental evidence has been obtained, to our knowledge) beam pattern quality are among of them.

Two types of HEB mixers are distinguished. First, phonon-cooled HEB mixers (NbN and NbTiN superconducting films based), where the hot electrons are cooled via inelastic scattering by phonons and consecutive hot phonons escape into the substrate. For thin NbN films the electron- phonon scattering time was measured to be about 10 ps at 10 K and the temperature dependence $\tau_{e\text{-}ph} \propto \theta^{-1.6}$ was observed [5]. The escape time depends on film thickness (d) and acoustic transparency (α) of the film-substrate interface, $\tau_{esc} \propto d/\alpha$. The detailed investigation of the NbN HEB mixers gain bandwidth for the wide range of NbN film thickness has been done in [6]. τ_{esc}=12d was estimated for silicon and sapphire substrates, where τ_{esc} is in ps and d is nm. While τ_{esc}=6d was found for MgO substrates [7]. For 3.5 nm thick NbN film the gain bandwidth of 3.5-4.5 GHz was found in the minimum mixer noise temperature bias point. Extension of the gain bandwidth up to 7-9 GHz has been observed for NbN HEB mixers at higher bias voltages, however the noise temperature increases in this case. Gain bandwidth of 2-2.5 GHz was measured for NbN HEB mixers on quartz substrate, which are used for WG receivers. The choice of quartz is made due to the relative small dielectric constant and ability to fabricate small and thin mixer chips for integration into terahertz mixer blocks. Recently, the gain bandwidth of NbN HEB mixers on quartz was extended up to 3.2 GHz by application a buffer layer of MgO [8].

In short Nb bridges (less then 0.5 μm long) the electron out- diffusion from the bolometer into the contact pads is the dominant cooling process for hot electrons. The electron diffusion time is $\tau_{diff} \propto \sqrt{L}$. For 0.1 μm long bolometer the mixer gain bandwidth as wide as 9 GHz was reported in reference [9]. Effect of the bias voltage on the gain bandwidth, similar to the NbN HEB mixers, has been reported in reference [10].

In this paper we report a quasioptical phonon- cooled NbN HEB mixer on silicon substrates. The main purpose is the development of a low noise mixer for the Herschel Space Observatory (Band 6L, 1.4-1.7 THz). We describe the technology used for fabrication of the HEB mixers, receiver noise temperature measurements in the 1-8 GHz IF band for LO frequencies 0.6 THz, 1.1 THz, 1.6 THz and 2.5 THz. FTS measurements of a double slot antenna integrated NbN HEB mixer is also presented.

2. Sample description and set- up.

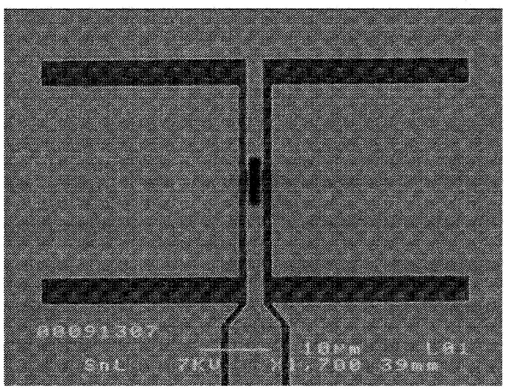
NbN film was deposited on high resistive silicon (≥3000 Ohm, 100- crystal orientation) substrates by dc reactive magnetron sputtering [6]. The substrate temperature during deposition was 850°C and the background pressure was 3×10^{-6} mbar. The Ar pressure was 9×10^{-3}mbar and N pressure was 2×10^{-4}mbar. The discharge current was 300 mA what provided the deposition rate of 0.45 nm/sec. For 3.5 nm thick films the sheet resistance was 400-500 Ohm/sqr, Tc=8.5-10 K. The gold antenna structure (either double- slot or logarithmic spiral) was made in 4 steps of e-beam lithography plus lift- off. The NbN film etching was done by the Ar ion- milling (400 V, 200 mA). The double- slot antenna integrated HEB mixer is shown in Fig.1. The bolometer size was 4 μm wide and 0.4 μm long.

For the mixer noise characterization, the standard Y-factor technique was used. The mixer was attached to the back side of 12 mm elliptical silicon lens. The mixer block, bias- T, isolator and IF amplifier were mounted into a LHe vacuum cryostat. The cryostat with 1-2 GHz IF chain has a Zitex G108 IR filter and HDPE (1mm thick) window. The cryostat with 4-8 GHz IF chain has the Zitex G108 IR filter and Teflon (1mm thick) window. A tunable from 1 GHz to 10 GHz Yig- filter with 30-50 MHz band was used after the room amplification stage. 12 μm Mylar beam splitter was 20 cm away from the cryostat window. The measurements are done at room conditions.

At 0.6 GHz and 1.1 THz two BWOs were used as LO sources, while at 1.6 THz and 2.5 THz an optically pumped FIR laser was applied.

The optimal LO power was dependent on the critical current and was at the level of 150-250 nW. The bias voltage was set to 1 mV, where the maximum Y factor was observed.

For the receiver noise temperature evaluation we used Callen- Wellton formula of the noise power radiated by a black body. The physical temperature of the hot and cold loads were 295 K and 77 K (LN).



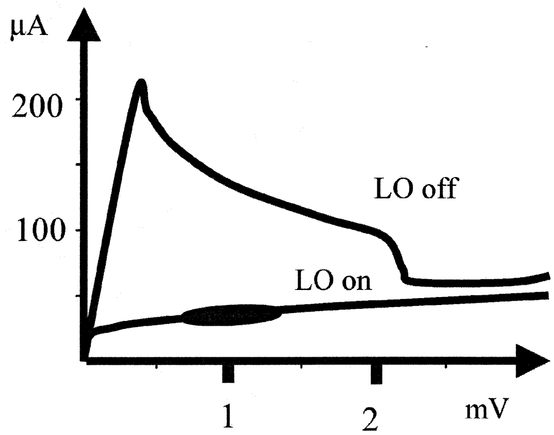


Fig.2. Typical IV- curves of a 4x0.4mm^2 NbN HEB mixer. The marked area points the minimum noise temperature bias points.

The double slot antenna (DSA) geometry was: the slot length is $0.3\lambda_0$, the slot separation is $0.17\lambda_0$, and the slot width is $0.02\lambda_0$, where λ_0 is the free space wave length of the middle of the antenna band. The coupling of the slots to the bolometer occurs via a CPW line (4 μm center conductor with 2 μm slots). RF block filter in the IF line contains 3 high impedance and 3 low impedance 1/4 λ_0 sections (not shown in the picture).

Two typical IV- curves at 4.2 K, one without and one with LO power, are shown in Fig.2. The optimal bias point (marked in the figure) was chosen in terms of the lowest mixer noise temperature and stability of the mixer output noise. The typical bias voltage is about 1 mV for all 4 μm wide and 0.4 μm long bolometers. The bias current in the optimal point depends on the mixer critical current (LO is off). For the critical current in the limits 190 μA to 400 μA the optimal bias current is from 30 μA to 50 μA.

3. 1.6 THz receiver.

In this chapter we report on the NbN HEB mixer sensitivity at 1.6 THz LO frequency, which is roughly in the middle of the Band 6L of the heterodyne instrument of the Herschel Space Observatory. The choice of this frequency for the test was made because of the availability of the strong laser generation line (LO source). Tunable LO sources in this frequency band are still under investigation [11, 12].

A compact (envelope of $32x32x45mm^3$), light- weight (<75 g) quasioptical mixer block was designed (see Fig.3) , which contains a low noise filter circuitry, ESD protection, IF readout, DC bias input.

However, the results presented here were obtained still with a prototype mixer block, described in the Chapter 2.

An investigation of the coupling efficiency to double slot antenna integrated Nb diffusion cooled HEB mixers has been reported in [13]. A discrepancy between the center frequency calculated from the quasi-static approach and the measured one was observed above 1 THz. The discrepancy increased towards higher frequencies.

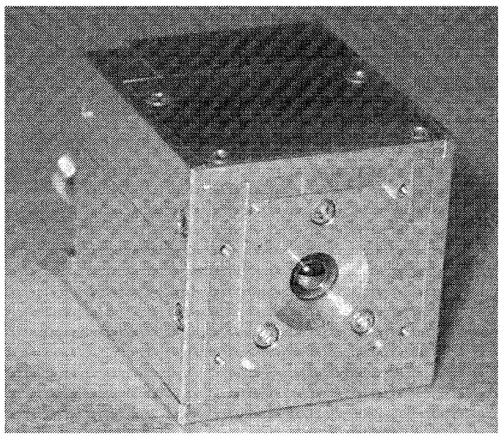


Fig.3. 1.4-1.7 THz NbN HEB mixer for the Herschel Space Observatory. The complete structure is made of aluminum. 5 mm Si lens is visible on the front side.

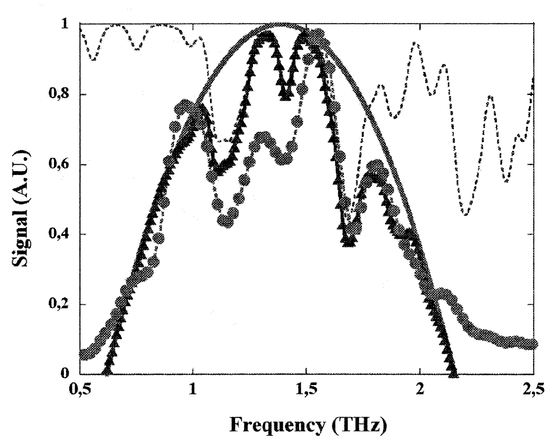


Fig.4. Direct response of 1.6 THz double-slot antenna integrated NbN HEB mixer

However, there has not been any data reported about NbN HEB coupling to DSAs. In Fig.4 (circles) we present a direct response of an NbN HEB mixer obtained with a Fourier Transform Spectrometer (FTS). Details of the measurements are presented in [14]. The antenna geometry used in the experiment is described in Chapter 2. Impedance of each slot in the second resonance is 45 Ohm [15] and is transformed to 55+7j Ohm via the CPW line down to the bolometer, positioned in the middle between the slots. The slots are connected in series with the bolometer. Therefore, the antenna embedding impedance at the bolometer terminals is 114+14j Ohm. Since the bolometer impedance is real ($\nu>2\Delta/h$, where Δ is the superconducting energy of the NbN film under the strong LO radiation) and is about 100 Ohm, the efficient radiation coupling occurs in a wide frequency range. Since the FTS measurements were carried out in the air, the antenna response is strongly affected by the water vapor absorption. Although vacuum measurements are necessary for correct antenna bandwidth estimations, certain conclusions can be made from the existing data. First, the atmosphere transmission of 30 cm path length have been calculated (22 °C, 30 % humidity) with 70 GHz resolution (Fig.4, dashed line). Assuming the antenna response spectrum to be parabolic (solid line), centered at 1.4 THz, and interpolating it with the atmosphere transmission spectra, we obtain a good correspondence between the resulted curve (triangles) and the measured one (circles). Then, 3 dB full bandwidth can be estimated to be 1.1 THz, i.e. 80 %. At 1.3 THz the measured response was not possible to approximate with a simple parabolic response of the antenna. A possible reason of this distortion can be a more complicated HEB response spectra then a simple parabola. For example, a secondary response peak at around 1 THz with a more sharp peak around 1.5 THz. More investigation is necessary to clarify this issue.

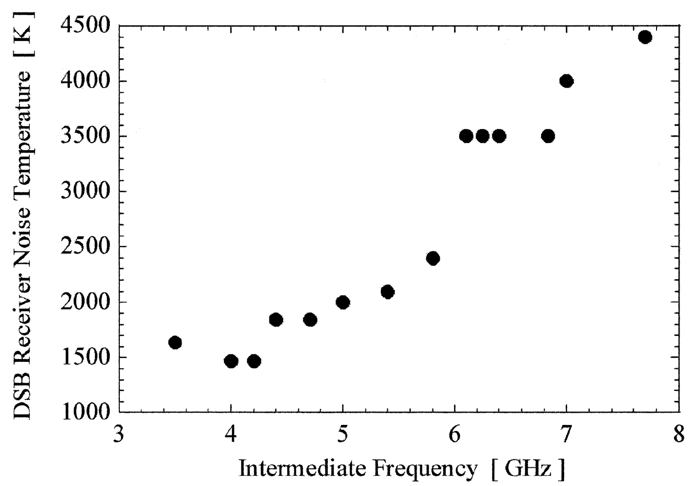


Fig.5 NbN HEB receiver DSB noise temperature at 1.6 THz LO frequency, from 3 GHz to 8 GHz.

The DSB receiver noise temperature was measured in the 3-8 GHz IF band. The lowest Tr value in this band is 1450 K at 4.2 K bath temperature. 28 μm thick Parylene was deposited onto the silicon lens as an antireflection coating [16]. The rise of the noise temperature from 4 GHz to 8 GHz is caused by the decrease of the HEB mixer gain. It has been shown at 600 GHz LO frequency, that the 3 dB gain roll- off frequency for HEB mixers made of 3.5 nm NbN film on silicon substrate [6] is 3.5 GHz. It means, that at 4 GHz there is 3 dB loss more than at 1.5 GHz, where the noise temperature of 700 K we have reported in the reference [16].

The HEB receiver noise bandwidth f_{0N} , which is defined as the intermediate frequency where the receiver noise temperature increases twice from its value at low IF, can be estimated as $f_{0N} \approx f_0 \cdot \sqrt{\dfrac{T_{out} + T_{IF}}{T_J + T_{IF}}}$ [17], where $T_{out}=T_{fl}+T_J$. T_{fl} and T_J are the electron temperature fluctuation noise and Johnson noise contributions to the mixer output noise, f_0 is 3 dB gain drop frequency, T_{IF} is the noise temperature of the IF chain. T_{IF} is about 5-6 K. Using the Nyquist theorem one can show that T_J approximately equals the electron temperature, which is close to T_c [17]. From the measured data for T_{out} (about 60 K [18]) one ends up with the ratio $f_{0N}/f_0 \approx 2$ for these HEB mixers. Therefore, the receiver noise temperature of 1500 K shall be expected at around 7 GHz. However, from Fig.5 one can see that at 7GHz Tr is 3500 K, i.e. at least twice higher of the expected value.

As it was described in Chapter 2, the cryostat window in the 3-8 GHz receiver cryostat was Teflon, which is more lossy in the terahertz range than the HDPE window, used in the 1-2 GHz receiver. However, about 2000 K of the rise of the noise temperature (3500 K- 1500 K) can be explained only with L additional loss at 300 K physical temperature: 300x(L-1)+ 1500 K x L=3500 K, i.e. L= 2.1 (3 dB) . 3 dB is a significant increase of the input loss to be attributed just to the Teflon window.

Thus, does the HEB mixer gain bandwidth decrease as LO frequency growths? The answer can be given only by direct gain bandwidth measurements at terahertz frequencies.

4. Spiral antenna integrated NbN HEB receiver

A direct comparison of the NbN HEB mixer performance in wide both RF and IF bands was done with a mixer, integrated with a logarithmic spiral antenna [19] on silicon substrate. The SEM image of the sample is given in Fig. 6. RF bandwidth of the spiral antennas in the terahertz range has been discussed in [20]. The upper and the lower frequencies are determined by the inner and the outer cut- off radii of the spiral. In our case it is about 10 μm and 100 μm correspondingly.

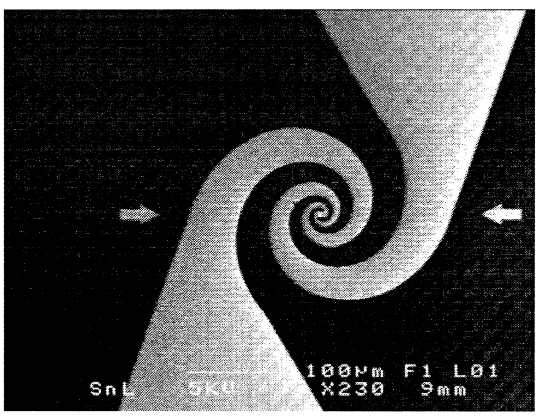


Fig. 6 SEM image of a logarithmic spiral antenna integrated HEB mixer on silicon. Dark area is the silicon surface, while the gray area is the gold antenna structure.

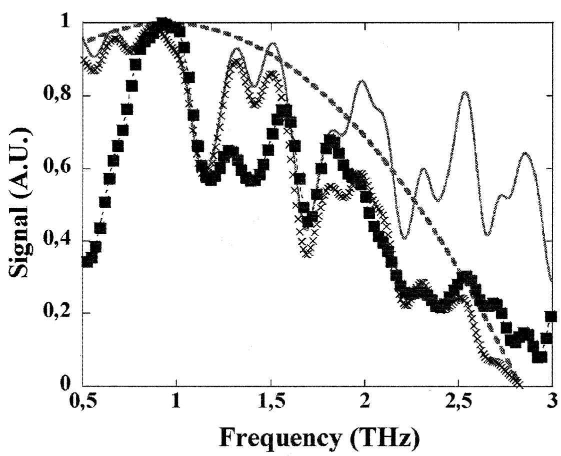


Fig.7. Direct response of the spiral antenna integrated NbN HEB mixer (squares), calculated transmission of the atmosphere between the FTS and the cryostat (solid), simplified parabolic spiral antenna response (dashed) and the interpolation of the parabola with the atmosphere transmission curve (crosses).

Although spiral antennas have been extensively used with HEB mixers during last years, to our knowledge there has been no experimental investigation done of their input bandwidth. In Fig. 7 we present a direct response of the spiral antenna integrated NbN HEB mixer from 0.5 THz to 3 THz obtained with a Fourier Transform Spectrometer (FTS). As for the double slot antenna FTS measurements, the response spectrum in Fig. 7 is modified by the water vapor absorption. Approximating the spiral antenna response by a simple parabola (Fig.7, dashed line) (the same as we did in Chapter 3), and by interpolating it with the atmosphere transmission curve, we obtain a curve (Fig.7, crosses) which is in a good agreement with the measured one (squares) from 1 THz up to 2.5 THz. Sharp roll- off of the response below 1 THz can be associated with the lower cut-off of the spiral antenna band. At higher frequencies the response decays slowly, what can be rather determined by the antenna conductive losses and the large dispersion of the terahertz waves in the spiral antenna structure. The higher frequency cut- off, caused by the spiral discontinuity in the antenna apex, seems to occur at frequencies above 3 THz, where the detected signal was already below the noise level of the measurement system. Regardless of the air loss effect, the efficiency of the presented antenna is quite low above 2 THz. We continue the planar antennas investigation in the terahertz range and the result will soon presented.

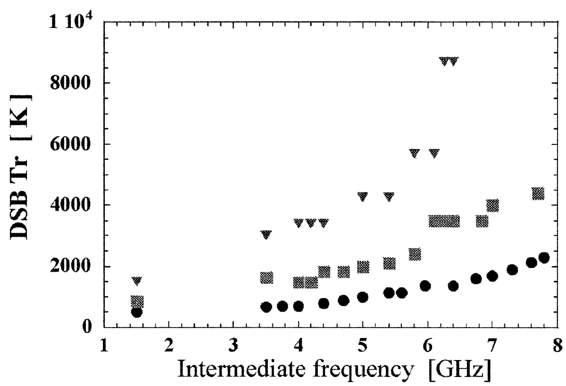


Fig.8 DSB receiver noise temperature of the NbN HEB mixer at 0.6 THz (circles), 1.62 THz (squares) and 2.5 THz (triangles) LO frequencies. Bath temperature is 4.2 K).

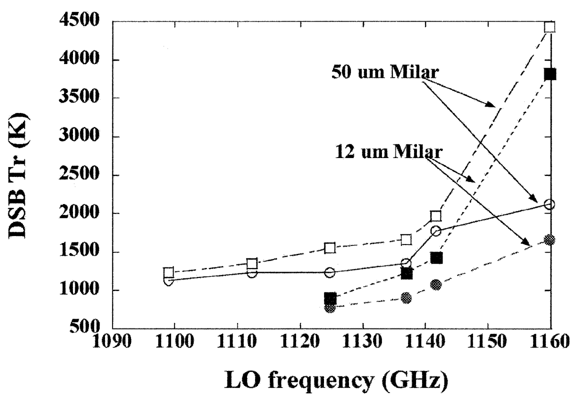


Fig.9 DSB receiver noise temperature at 1.5 GHz IF with 12 μm (filled) and 50 μm (open) Mylar beam splitters. Circles correspond to the 30 cm optical path length, while squares correspond to the 60 cm optical path length.

Fig. 8 shows the DSB receiver noise temperature for 4x0.4 μm size HEB mixer integrated with the spiral antenna in the intermediate frequency band from 1 GHz to 8 GHz. The minimum Tr values were 500 K, 800 K and 1500 K at 0.6 THz, 1.62 THz and 2.5 THz LO frequencies. The measurements were done at 4.2 K bath temperature. For the measurements at 1.6 THz and 2.5 THz silicon lenses were coated with 28 μm and 19 μm thick Parylene layers correspondingly. The noise bandwidth can be estimated from Fig.8 as 5 GHz at 0.6THz and 1.6 THz, and 4 GHz at 2.5 THz.

The frontier of the SIS and HEB heterodyne receivers falls to roughly 1.1-1.2 THz. This is the highest frequency, where an SIS receiver operation has been reported [21]. Nb- SIS mixers with Al tuning circuit has shown 840 K of the DSB noise temperature at 1.042 THz. Recently, the noise temperature of 380 K at 1.13 THz was achieved [22] for Nb/AlN/NbTiN SIS mixers with an all-Au tuning circuit. Therefore, it was interesting to compare directly two existing technologies. We used the same HEB mixer (with the spiral antenna), that we discussed in this Chapter, to perform noise measurements at 1.1 THz. The lowest DSB noise temperature in this range was 780 K (Fig.9, filled circles). We should note, that Si lens did not have any antireflection coating during these measurements, what introduced about 1 dB reflection loss on the lens surface. A sharp increase of the noise temperature towards 1.16 THz is caused by the water absorption line, since the measurements were done in the air. With a withdrawal of the hot/cold load 30cm further from the cryostat, the influence of the water absorption increases drastically. Below 1.125 THz the output power of the LO was not enough to pump the mixer to the optimal point with a 12 μm thick Mylar beam splitter. Therefore, we exchange it for a 50 μm thick Mylar beam splitter. While the receiver noise temperature was higher in this case, it was still lowering down to 1.10 THz (open circles). Since there is already another water line at 1.1 THz which we do not observe in Fig. 9, we conclude that we have an error in the LO frequency estimation. The wavelength- meter, used for the frequency estimation, seemed to have about 60 GHz up- shift and, in fact, the frequencies in the Fig.9 might be about 60 GHz higher of the actual radiation frequency. Receiver noise temperatures with the 50 μm thick Mylar beam splitter and 60 cm of the optical path length are shown with the open squares.

5. Conclusion.

Quasioptical NbN HEB mixers, discussed in this paper, showed very good performance from subMM to terahertz frequencies. In Fig. 10 we summarize the obtained DSB receiver noise temperatures quoted in the present paper as a function of the LO frequency. These data include all input losses and the IF chain noise. The solid line represents the 10 $h\nu/k$ noise level, where h is the Plank constant, ν is the LO frequency, k is the Boltzman constant. With the introduction of the AR coating the noise level at 0.6 THz -1.1 THz range is expected to drop to the level marked with the dashed line. As we have shown, at terahertz frequencies the planar antenna performance deviates from the calculations given by the quasi-static approach. Specifically for DSA integrated NbN HEB mixers the measured center frequency is lower than calculated one, as it has been shown for Nb diffusion cooled HEB mixers. Now we can conclude that the reason of the down- shift of the center frequency is caused not by the bolometer geometry, as it was suggested, but by the antenna structure itself. The spiral antenna performance, used in the investigation, is not optimized for the frequencies above 2 THz either. The FTS investigation of the downscaled spiral antennas (with smaller inner radius) performance has to be performed for the 2.5 THz receiver.

From 0.6 THz to 1.6 THz the receiver noise bandwidth is about 5 GHz for NbN HEB mixers on silicon substrate, which is about 2 GHz lower than it was expected from the gain bandwidth data. At 2.5 THz the receiver noise bandwidth is 4 GHz. One possible explanation of that can be higher input losses during measurements in the 3-8 GHz IF band comparing to the measurements in the 1-2 GHz band.

We conclude that optimization of the planar antennas will lead to an improvement of HEB mixers performance above 1 THz.

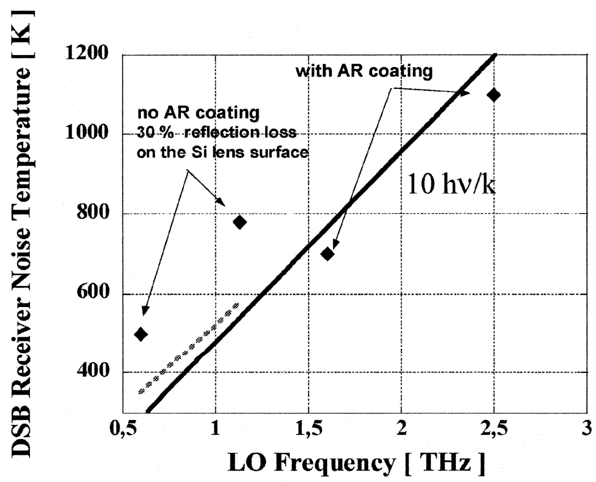


Fig.10 Summary of NbN HEB mixer performance versus LO frequency. The solid line notes the 10 hν/k noise level. Dashed line represents the expected noise temperatures in the 0.6-1.1 THz band with introduction an AR coating for Si lens.

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