IF Bandwidth of Phonon Cooled HEB Mixers Made from NbN Films on MgO Substrates

S. Cherednichenko*, M. Kroug, P. Yagoubov, H. Merkel, E. Kollberg
Chalmers University of Technology, S-412 96 Gothenburg, Sweden

K.S. Yngvesson
University of Massachusetts, Amherst, USA

B. Voronov, G. Gol'tsman
Moscow State Pedagogical University, Moscow, Russia

*serguei@ep.chalmers.se

Abstract

An investigation of gain and noise bandwidth of phonon-cooled hot-electron bolometric (HEB) mixers is presented. The radiation coupling to the mixers is quasioptical through either a spiral or twin-slot antenna. A maximum gain bandwidth of 4.8 GHz is obtained for mixers based on a 3.5 nm thin NbN film with T_c=10 K. The noise bandwidth is 5.6 GHz, at the moment limited by parasitic elements in the device mount fixture. At 0.65 THz the DSB receiver noise temperature is 700-800 K in the IF band 1-2 GHz, and 1150-2700 K in the band 3.5-7 GHz.

Introduction

The ongoing development of superconducting hot electron bolometric (HEB) mixers at THz frequencies is mainly driven by the need in radio astronomy for low noise and wide band heterodyne receivers.

Quasi optically coupled HEB mixers have been tested at frequencies up to several THz. Both the diffusion-cooled type, based on Nb, and the phonon-cooled type, based on NbN, have shown excellent results in terms of sensitivity. In the band between 1 THz and 2.5 THz the DSB receiver noise temperature is roughly 20 times the quantum limit which is much better than competing technologies such as Schottky diodes or SIS mixers [1- 5]. In addition, HEB mixers require much less local oscillator (LO) power than Schottky-mixers, typical is 50-300 nW depending on the bolometer size and critical current [6]. The gain bandwidth (f_0) of diffusion-cooled mixers based on very short ($L \leq 0.1$ um) Nb bridges has been measured to be 9 GHz [7]. The best result for phonon-cooled mixers was so far 3.5-4 GHz, obtained with devices made from ultrathin (d=3 nm) NbN films on sapphire substrates [8].

The maximum gain bandwidth of HEB mixers is set by the electron temperature relaxation time $f_0=(2\pi\tau_\theta)^{-1}$. A detailed study of electron dynamics in superconducting films under modulated electromagnetic radiation was done in [9]. For the phonon cooled type, τ_θ is a complicated function of several parameters: the electron-phonon interaction time τ_{e-ph}, the ratio of the specific heats c_e/c_{ph} and the escape time τ_{esc} of phonons from the film to the substrate.

As was shown earlier, for NbN $\tau_{e-ph}\propto\Theta^{-1.6}$ and at 10 K τ_{e-ph} equals 12 ps [10]. The escape time depends on film thickness (d) and acoustic transparency (α) of the film-substrate interface, $\tau_{esc}\propto d/\alpha$. In the limit of ultrathin NbN films, d=3-5 nm, τ_{e-ph} and τ_{esc} are of the same order of magnitude, and both time constants must be minimized in order to achieve a short electron relaxation time τ_θ. Therefore, NbN films with a high critical temperature T_c and good thermal coupling to the substrate are needed for large gain bandwidth.

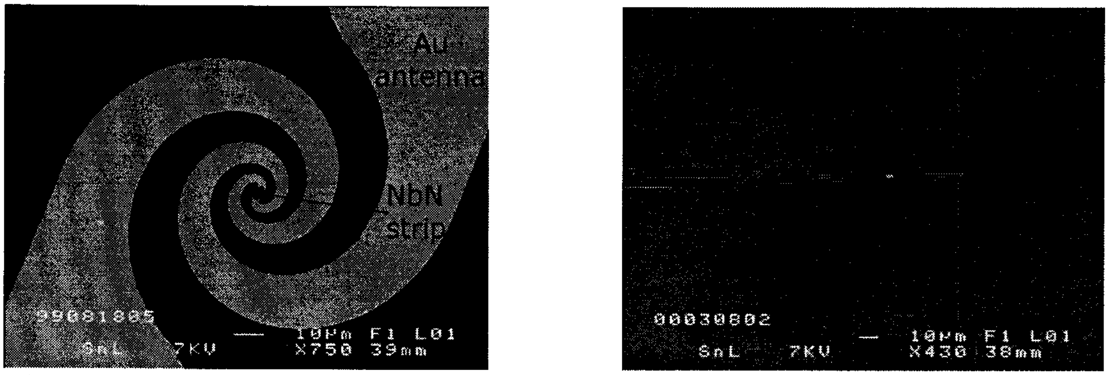
Recent experiments showed that crystalline MgO as a substrate provides high quality NbN films with a phonon escape time which is two times shorter compared to films on Si or sapphire substrates [1]. An estimate based on [9] shows that 3 nm thin films on MgO with T_c=10 K would allow for 5-6 GHz gain bandwidth.

Following this suggestion, HEB devices with film thickness 3.5 nm and 5 nm have been fabricated and characterized. The results for the mixer gain bandwidth are close to the predicted values. Ongoing work is now aimed at optimization of film technology in the limit of 3 nm thin films.

For practical application of HEB mixers one wishes to maximize the receiver noise bandwidth, f_{0N},. defined as the frequency band over which the receiver noise temperature stays within 2 times of its minimum value. A special feature of HEB mixers is the fact that f_{0N} may be 2-3 times larger than the gain bandwidth This is because the dominating noise source in HEB mixers is thermal fluctuation noise, which has the same IF frequency dependence as the conversion gain [14]. This makes its contribution to the input noise temperature of the mixer independent of the IF frequency. The final goal of the project is to optimize f_{0N}. Here we present the first results from receiver noise temperature measurements in the 4-8 GHz band. We also show that a noise bandwidth of up to 10 GHz can be realized.

Devices and Experimental Set-up

NbN films are deposited by dc magnetron sputtering on MgO substrates heated up to 850 °C. Standard lithography techniques are used to pattern a NbN micro bridge integrated with a planar Au antenna. Details of the fabrication process can be found in [11]. HEB devices from three batches, labeled M2, M7 and M8, have been investigated; the device parameters are summarized in Table 1. Both a self complementary spiral and twin-slot antennas are used (see Fig. 1).



a) b)

Figure 1. SEM micrograph of the antenna integrated mixers: (a) Selfcomplementary spiral (b) Twin-slot.

The measurement set-up is presented in Fig.2. For gain bandwidth measurements two backward wave oscillators (BWO) serve as LO and signal sources. The beams are focused by two Teflon lenses and combined by a 12 µm thick Mylar beamsplitter. The cryostat is equipped with a Teflon window and a cooled 350 µm Zitex G115 IR filter. The mixer is mounted onto a 12 mm diameter Si elliptical lens. The IF chain consists of a broadband bias-T followed by a two stage Miteq amplifier (0.1-20 GHz). With a second mixer the IF signal is down-converted to the 0-50 MHz band and measured by a power meter.

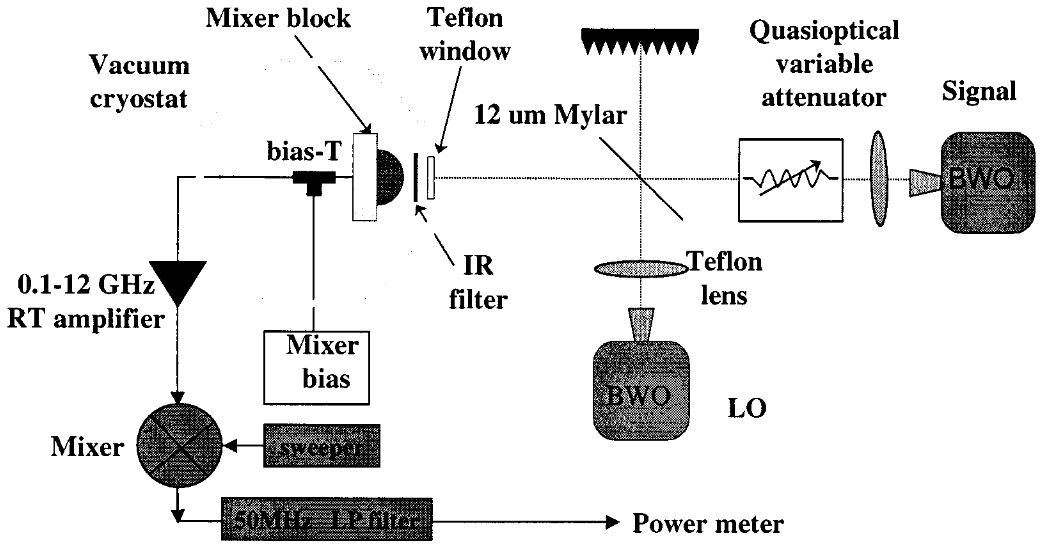


Figure 2. Measurement set up for gain bandwidth measurements.

The DSB receiver noise temperature T_r is measured using the Y-factor technique with blackbody loads at 300 K and 77 K in the signal path. Two different cooled IF amplifiers with equivalent noise temperatures T_{IF}=5 K (1-2 GHz) and T_{IF}=5-10 K (4-8 GHz) are used in this case. Further amplification and signal registration is done in the same way as described above.

The mixer output noise temperature T_{out} is obtained by measuring the ratio of the receiver output noise power with the mixer in the operating point and in the superconducting state [12].

Gain bandwidth measurements

The mixer gain bandwidth was measured for devices from three batches (M2, M7 and M8) with film thicknesses 5 nm and 3.5 nm. The mixer operating conditions in terms of dc bias and LO power are the same that yield the lowest receiver noise temperature.

The values obtained for the mixer gain bandwidth are: 4.5-4.8 GHz for the mixers based on a 3.5 nm NbN film with Tc = 10 K (batch M7); 2.8 GHz for the mixers based on a 3.5 nm NbN film with Tc =8.5 K (batch M8); 3 GHz for the mixers based on a 5 nm NbN film with Tc = 8.5 K (batch M2).

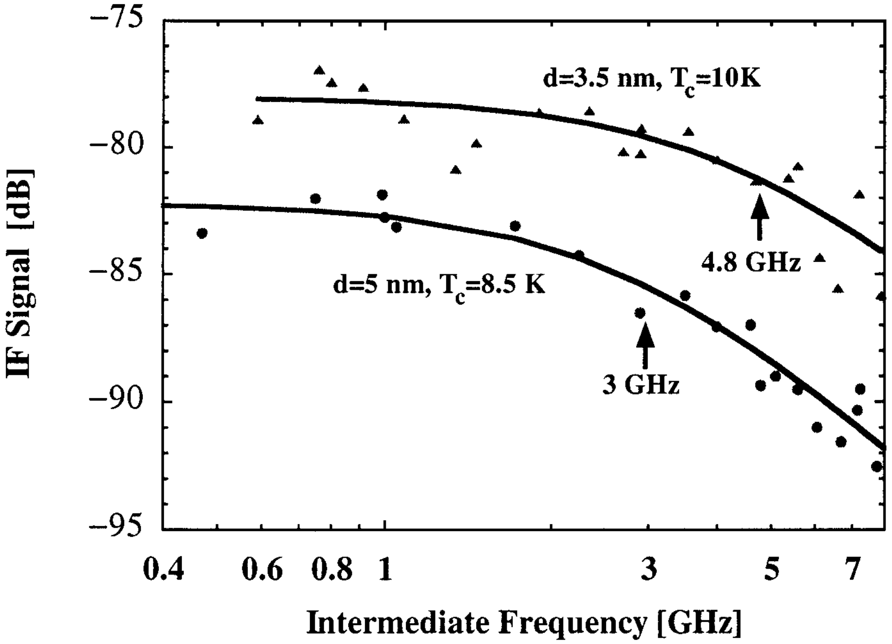


Figure 3. IF signal vs frequency for the mixers M2-1 and M7-7.

The detected signal vs. intermediate frequency for the mixers M2-1 and M7-7 is plotted in Fig. 3.

As was shown in [8] the two-temperature model, which was introduced in [9], can be successfully used for estimation of the HEB mixer IF bandwidth. Within this model the major tendencies of the gain bandwidth can be derived. Using the data of $\tau_{e-ph}=0.4\cdot\Theta^{-1.6}$ (ns) [13] and $\tau_{esc}=6\cdot d$ (ps), where d is in nm, [1], we calculated the gain bandwidth of NbN HEB mixers on MgO versus the electron temperature for different film thickness (Fig. 4). It can be seen from the picture that a gain bandwidth up to 6 GHz can be realized for 3 nm thick NbN films with $Tc \geq 12$ K. The temperature dependence of the gain bandwidth at low electron temperature values and the weak dependence on the film thickness means that the electron-phonon interaction is the bottleneck of the electron cooling process. With an increase of the electron temperature the electron-phonon interaction becomes fast enough to provide rapid heat transfer from electrons to phonons. Under such conditions the phonon escape time becomes the bottleneck and the gain bandwidth is a function of the film thickness only. For each film thickness there is a maximum value of f_0, which can be reached when Θ exceeds a certain value. A decrease of the film thickness can even result in a decrease of f_0 if Θ drops much.

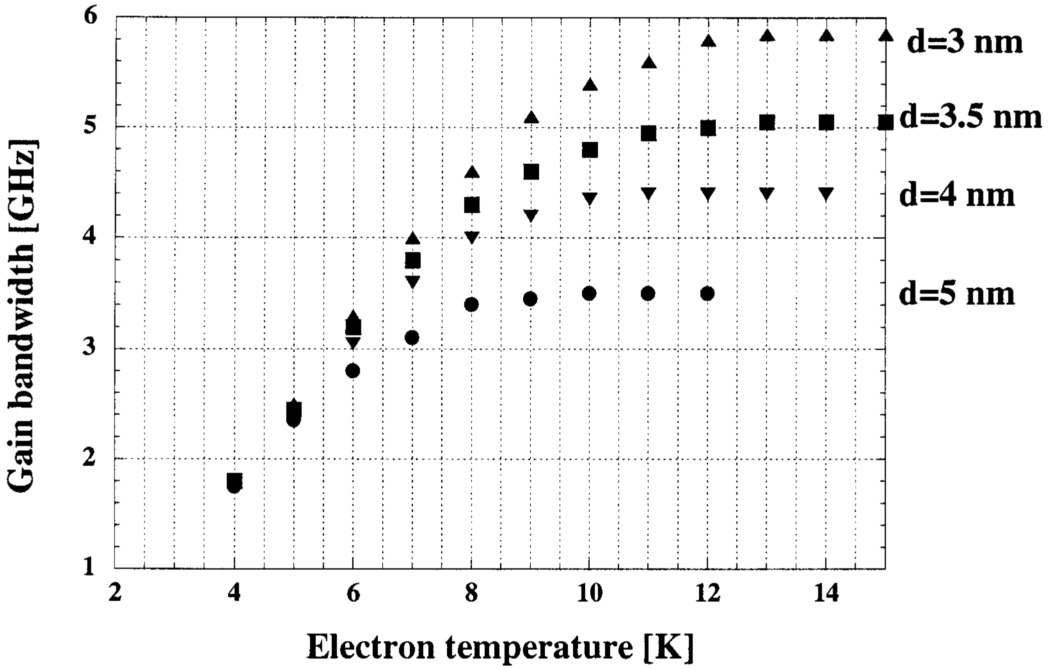


Figure 4. IF bandwidth of NbN phonon-cooled mixers according to the two temperature model.

Table 1. Device parameters and measurement results: Film thickness d, critical temperature T_C bolometer length L and width W, critical current I_C and, DSB receiver noise temperature T_r, mixer output noise temperature T_{out}, intrinsic mixer loss L_m, and mixer gain bandwidth f_0.

Device number	d, nm and T_c, K	WxL, μm^2	I_c, μA	T_r, K 1.5 GHz	T_r, K 4 GHz	L_m, dB 1.5 GHz	T_{out}, K 1.5 GHz	f_0, GHz
M2-1	5, 8.5	4x0.4	435	530	1150			3
M7-5	3.5, 10	2x0.1	290	750				4.5
M7-7	3.5, 10	2x0.1	210					4.8
M7-9	3.5, 10	2x0.3	300	850	1150	10.4	57	4.5
M7-10	3.5, 10	2x0.3	290	850^*	1100	10.4^*	57^*	
M7-13	3.5, 10	2x0.3	260	850	1370	9.2	75	
M8-1	3.5, 8.5	4x0.4	107					2.8
M8-9	3.5, 8.5	2x0.3	120	980				2.5

* values are extrapolated from mixer M7-9

Receiver Noise Temperature

The receiver noise temperature was measured in the 1-2 GHz and 3.5-8 GHz bands. The best values of the DSB receiver noise temperature at 1.5 GHz are 530 K, 750 K and 980 K for batches M2, M7 and M8 respectively. According to our estimates the optical losses of the receiver are 4 dB.

Most of the mixers are integrated with a self-complementary spiral antenna which has been shown to work well from 0.5 THz up to 3 THz. We also used a twin-slot antenna designed for 600 GHz (sample M7-13). Mixers with both antenna types showed the same performance.

By measuring the receiver output noise power with the mixer in the superconducting state and in the operating point ($U=P_{sc}/P_{op}$) one can calculate the mixer conversion loss L_m and the mixer output noise temperature T_{out}. Typical values for L_m are 9-10 dB, and for T_{out} 50 K to 80 K. The knowledge of T_{out} allows one to estimate the receiver noise bandwidth f_{0N} which is given by $f_{0N} \approx f_0 \cdot \sqrt{\frac{T_{out}+T_{IF}}{T_J+T_{IF}}}$, 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 [14], and T_{IF} is the noise temperature of the IF chain. Using the Nyquist theorem one can show that T_J approximately equals the electron temperature, which is close to T_c [14]. From the measured data for T_{out} one ends up with the ratio $f_{oN}/f_0=2\div2.5$ for these HEB mixers.

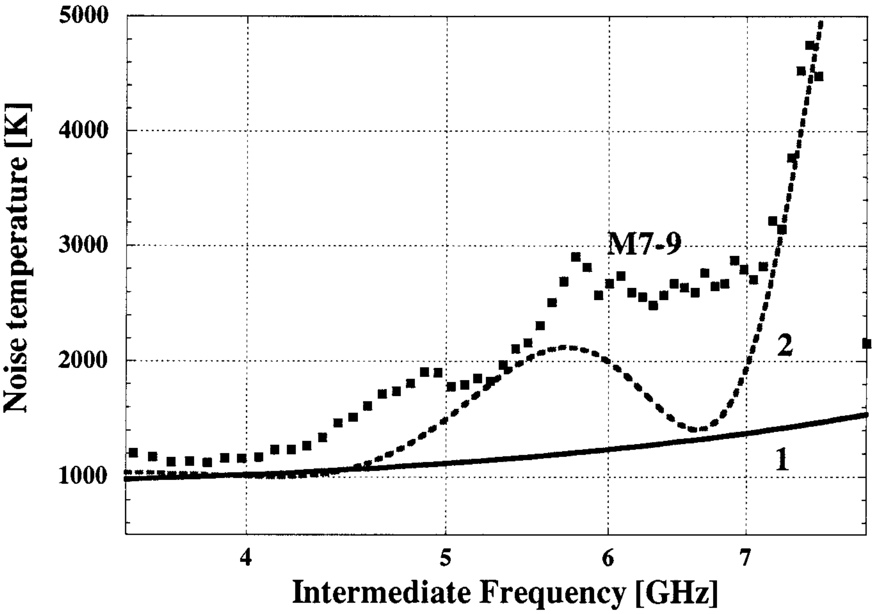


Figure 6. Receiver noise temperature in the 4-8 GHz band for device M7-9. Measured data (squares), calculations for ideal mixer mount (1) and coaxial mixer mount (2).

Using the data of L_m, T_{out} (obtained at $f_{IF}=1.5$ GHz) and f_0 for the mixer M7-9, T_r as a function of f_{IF} is calculated for the band 4-8 GHz (see Fig. 6, solid line 1). For this calculation the IF noise is $T_{IF}=6$ K, independent of frequency.

Measured data of $T_r(f_{IF})$ are represented by the squares. With T_r = 850 K at 1.5 GHz this yields a noise bandwidth of 4.6 GHz.

Since this value is quite different from the estimate, we used a vector network analyzer to characterize the mixer mount (the part of the IF chain between the mixer and the bias-T). The measurements were done at room temperature with an HEB device in place. At room temperature the device by itself behaves as a resistor with a value equal to the dc resistance. We found that at frequencies above 2 GHz the impedance of the mount develops a reactance and the real part of the impedance drops. As a result, the mixer becomes mismatched to the load, which leads to additional losses increasing with frequency $L_{mm}(f)$. Taking into account this function we calculated T_r vs f_{IF} again (Fig. 6 curve 2). Curve 2 is close to the measured data.

In order to improve the situation we replaced the semirigid coaxial cable in the mixer mount with a microstrip on a Duroid substrate. The measured receiver noise temperature for the mixer M7-10, which is very similar to M7-9, is shown in Fig 7 (triangles). The receiver noise bandwidth now equals 5.6 GHz but is still limited by the parasitics of the mixer mount. The dotted line represents the calculated T_r vs IF where the measured losses of the new mixer mount are inserted. From this figure follows that further improvements of the mixer mount are needed.

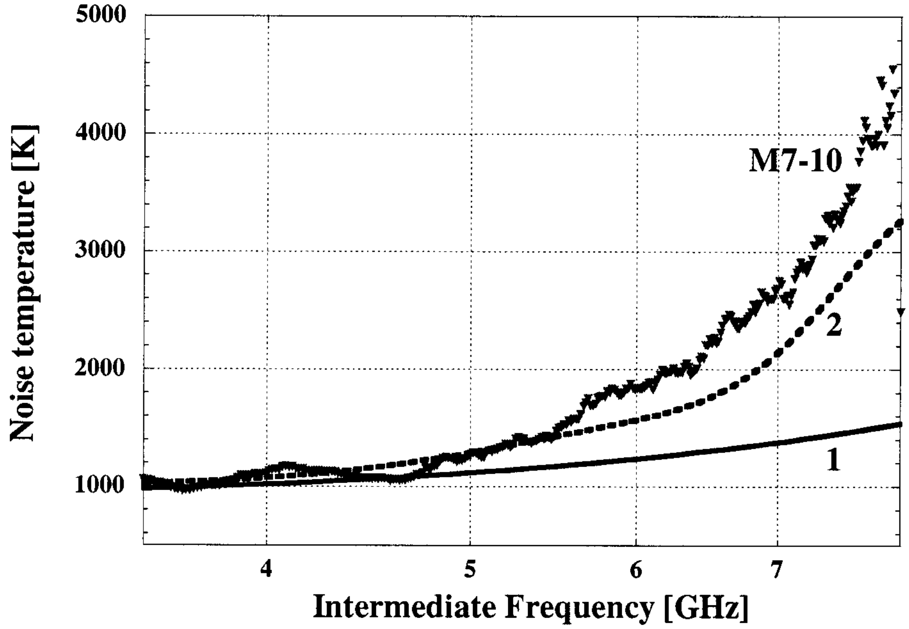


Figure 7. Receiver noise temperature in the 4-8 GHz band for device M7-10. Measured data (triangles), calculations for an ideal mixer mount (1) and the microstrip mixer mount (2).

Conclusion

We have fabricated and investigated phonon-cooled HEB mixers based on NbN films on MgO substrate. The maximum gain bandwidth 4.8 GHz was obtained for a 3.5 nm NbN film with T_c=10 K. The best DSB receiver noise temperature for these mixers was 750 K at 0.6 GHz. The first measurements of the receiver noise temperature for a NbN HEB mixer in the IF band 4-8 GHz were done. The receiver noise bandwidth is 5.6 GHz which is now limited by parasitics of the mixer mount. We expect that further improvement of the mixer mount may result in 9-10 GHz receiver noise bandwidth.

Acknowledgment

This work has been supported by Swedish Research Council for Engineering Sciences, Swedish National Space Board, ESA (ESTEC/No.11738/95/NL/MV) and INTAS project # 96-0268

References

---

1 P. Yagoubov, M. Kroug, H. Merkel, E. Kollberg, J. Schubert, H.-W. Huebers, S. Svechnikov, B. Voronov, G. Gol'tsman, and Z. Wang, "Hot Electron Bolometric Mixers Based on NbN Films Deposited on MgO substrates", *Proc. Europ. Conf. on Appl. Superconductivity (EUCAS'99),* Barcelona, 14-17 September, 1999.

2 P. Yagoubov, M. Kroug, H. Merkel, E. Kollberg, J. Schubert, H.-W. Huebers, G. Schwaab, G. Gol'tsman, and E. Gershenzon, "NbN Hot Electron Bolometric Mixers at Frequencies Between 0.7 and 3.1 THz", *Proc. 10th Int. Symp. on Space Terahertz Technology*, Charlottesville, VA, 214, 1999.

3 J. Kawamura, C.-Y. E. Tong, R. Blundell, D. C. Papa, T. R. Hunter, G. Gol'tsman, S. Cherednichenko, B. Voronov, and E. Gershenzon, "An 800 GHz NbN Phonon-cooled Hot-electron Bolometer Mixer Receiver", IEEE Trans. on Appl. Superconductivity, vol. 9, No 2, 3753, 1999.

4 A. Skalare, W.R. McGrath, B. Bumble and H. G. LeDuc, "Noise and RF bandwidth measurements of a 1.2 THz HEB heterodyne receiver", *Proc. 8th Int. Symp. on Space Terahertz Technology,* Cambrige, MA, 47, 1997.

5 R. Wyss, B. Karasik, W. McGrath, B. Bumble, H. LeDuc, "Noise and Bandwidth Measurements Of Diffusion-Cooled Nb Hot-Electron Bolometer Mixers at Frequencies Above the Superconductive Energy Gap", *Proc. 10th Int. Symp. on Space Terahertz Technology*, Charlottesville, VA, 214, 1999.

6 P. Yagoubov, M. Kroug, H. Merkel, E. Kollberg, G. Gol'tsman, S. Svechnikov and E. Gershenzon, "Noise temperature and local oscillator power requirement of NbN phonon-cooled hot electron bolometric mixers at Terahertz frequencies", *Appl. Phys. Lett.*, 73, 2814, 1998.

7 R. Wyss, B. Karasik, W. McGrath, B. Bumble, H. LeDuc, "Noise and Bandwidth Measurements Of Diffusion-Cooled Nb Hot-Electron Bolometer Mixers at Frequencies Above the Superconductive Energy Gap", *Proc. 10th Int. Symp. on Space Terahertz Technology*, Charlottesville, VA, 214, 1999.

8 S. Cherednichenko, P. Yagoubov, K. Il'in, G. Gol'tsman and E. Gershenzon, "Large bandwidth of NbN phonon cooled hot-electron bolometer mixers on sapphire substrates", *Proc. 8th Int. Symp. on Space Terahertz Technology*, Cambrige, MA, 245, 1997.

9 N.Perrin and C.Vanneste, Phys. Rev. B, **28**, 5150, 1983.

10 Yu. P. Gousev, G. N. Gol'tsman, A. D. Semenov, E. M. Gershenzon, R. S. Nebosis, M. A. Heusinger, and K. F. Renk, "Broadband Ultrafast Superconducting NbN Detector for Electromagnetic Radiation", J. Appl. Phys., vol.75, No 7, 3695, 1994.

11 M. Kroug, P. Yagoubov, G. Gol'tsman and E. Kollberg, "NbN quasioptical phonon cooled hot electron bolometric mixers at THz frequencies", *Proc. the 3rd. European Conference on Applied Superconductivity*, Veldhoven, Netherlands, (Inst. Phys. Conf. Ser. No 158, p.405), 1997.

12 H. Ekström, E. Kollberg, P. Yagoubov, G. Gol'tsman, E. Gershenzon and S. Yngvesson, "Gain and noise bandwidth of NbN hot-electron bolometric mixers", *Appl. Phys. Lett.* 70, 3296, 1997.

13 K.S.Il'in, G.N.Gol'tsman, B.M.Voronov, R.Sobolewski, "Charachterization of the electron energy relaxation process in NbN hot-electron devices", *Proc. 10th Int. Symp. on Space Terahertz Technology*, Charlottesville, VA, 390, 1999.

14 B.S.Karasik and A.I.Elant'tev, "Noise Temperature limit of a Superconducting Hot Electron Bolometer Mixer," App.Phys.Lett., vol.68, pp.853-855,1996.