REVIEW OF HEB HETERODYNE DETECTORS AND RECEIVER SYSTEMS FOR THE THz RANGE: PRESENT AND FUTURE (Invited talk)

Sigfrid Yngvesson

Department of Electrical and Computer Engineering
University of Massachusetts at Amherst, Amherst, MA 01003

I. INTRODUCTION

The field of Heterodyne THz detectors using the hot-electron effect in superconductors was initiated through the pioneering Russian work by Gershenzon et al. [1]. Their version of this general type of detector came to be distinguished as the PHEB ('Phonon-Cooled Hot Electron Bolometer') after Dan Prober [2] proposed what is now known as the DHEB ('Diffusion-Cooled Hot Electron Bolometer'). Since that time, both types of HEB devices have demonstrated the order-of-magnitude lowering of the receiver noise temperature, as measured in several laboratories at frequencies from 1 THz to 2.5 THz, which had been anticipated. HEBs have also been part of the history of these ISSTT symposia since the very first one, although one won't find an HEB session or even HEB mentioned in a title for a paper at the 1st ISSTT: The present author "hid" a discussion on HEBs employing the semiconductor 2DEG medium in a paper entitled: "Integrated Tapered Slot Antenna Arrays and Devices" [3]. The first talks on the superconductor version of the HEB appeared at the 4th ISSTT. Since the 5th ISSTT, there have been entire sessions devoted to HEB topics, typically two at each conference. To-day, HEB receivers for up to 1.46 THz have been installed on radio telescopes, and are beginning to produce significant astronomical data in this frequency range which has not been well exploited for heterodyne measurements previously. HEB detectors now being developed will be launched on Herschel and flown in SOFIA, and it is appropriate to ask what their real potential is for future such systems; for example, how high frequencies will they realistically be used for, what are the anticipated actual requirements for LO power, etc. This talk will review the present status of the THz HEB heterodyne detector field, and attempt to make predictions for where it will go in the future. For brevity, the review will be organized around specific questions, to which I will give answers which obviously represent my own personal opinion. I hope at least some of the answers and comments will give rise to fruitful discussions.

II. STATE-OF-THE-ART OF HEB HETERODYNE DETECTOR TECHNOLOGY

<u>A. Operating HEB systems above 1 THz.</u>

There are presently to my knowledge three operating HEB heterodyne receivers systems above 1 THz (this frequency ought to be the dividing line at a THz conference!):

1) Kawamura et al. at the SMTO, on Mt. Graham here at the U. of Arizona. [4]
2) TREND on AS T/RO at the South Pole, see Gerecht et al, this symp. (Figure 1) [5]
3) Radford et al, at Cerro Sairecabur, Chile. [6]

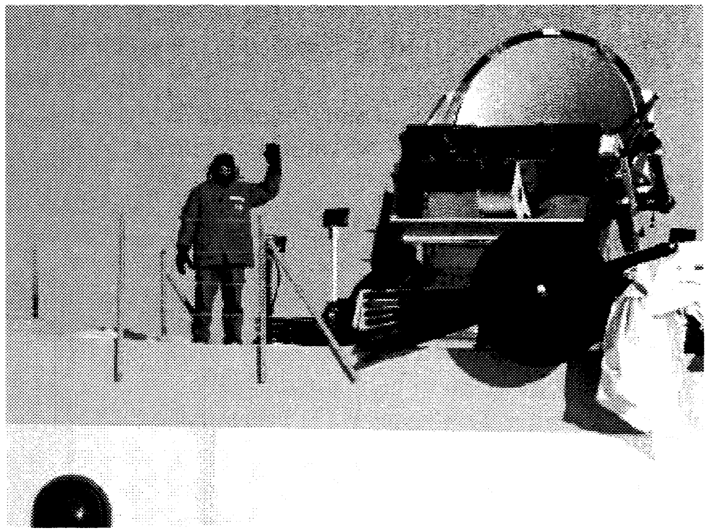

Figure 1. TREND at AST/RO

B. DSB Receiver Noise Temperature

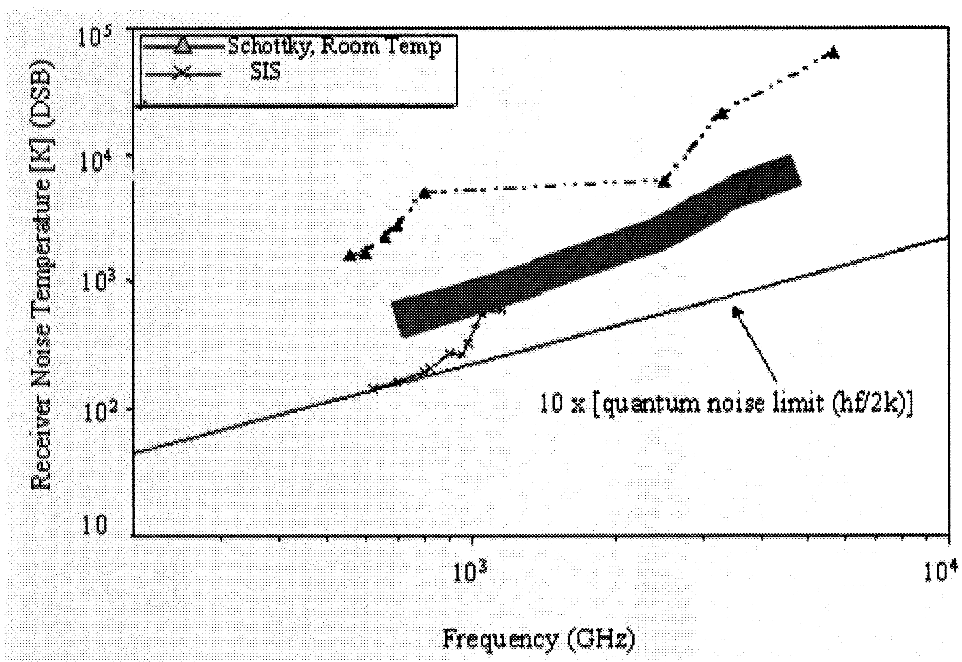

Figure 2. Representative DSB Receiver Noise Temperature Data from several Laboratories (the broad red band).

Figure 2 (above) reviews the state-of-the-art of DSB receiver noise temperatures (NTs) measured IN THE LABORATORY with HEB receivers.

The task is made easier by the fact that a number of laboratories have published NTs in about the same range, roughly within the red band in this figure.
The laboratories represented are listed in Table 1. Only PHEBs are presently represented among the operational systems on telescopes. The data above 2.5 THz (up to 5.3 THz) actually have only been demonstrated by a single program, the DLR/MSPU collaboration.

TABLE 1. Laboratories represented in Figure 1.

Laboratory	Type of HEB
Moscow State Pedagogical Univ. (MSPU), Moscow, Russia	PHEB, NbN, NbTiN
Chalmers Univ. of Technology (CUT), Göteborg, Sweden	PHEB, NbN, NbTiN
DLR Institute of Space Sensor Technology, Berlin, Germany	PHEB, NbN
SRON/Technical Univ. of Delft, The Netherlands	DHEB (Nb,Nb/Au), PHEB, NbN, NbTiN
KOSMA, Köln, Germany	DHEB (Nb), PHEB (NbTiN)
University of Massachusetts, Amherst and Lowell, MA, USA	PHEB, NbN
Yale University, New Haven, CN, USA	DHEB, Nb, Nb/Au, Al
Harvard/Smithsonian Center for Astrophysics, Cambridge, MA, USA	PHEB, NbN, NbTiN
National Institute for Standards and Technology (NIST), Boulder, CO, USA	DHEB, Nb
Jet Propulsion Laboratory, Pasadena, Ca, USA	DHEB, Nb, Ta; PHEB, NbTiN

C. HEB Receiver Systems "on the Way".
Some of the major HEB receiver systems which are under development are:
1) HIFI Band 6 (Herschel) 1.4 THz to 1.9 THz, CUT, JPL; Launch 2007; see Figure 3;
2) GREAT (for SOFIA), 1.4 THz to 5 THz, DLR, MPIfR, KOSMA, Operation 2005;
3) TELIS (balloon launched), 1.8 THz, DLR, SRON, RAL; First flight 2005.

We are clearly entering an era in which HEB low-noise receivers for up to at least 2.5 THz will be used in many systems. GREAT is also aimed at even higher frequencies, up to 5 THz. So, we can ask:

D) Will HEB receivers climb even higher in frequency?
Let's review why HEBs have always been considered promising for being extended to much higher frequencies than traditional technologies, such as Schottky diodes.

1) HEBs are "bulk" (or actually "surface") devices. Parasitic reactances are very small, even at the highest THz frequencies.
2) HEBs rely on a) being able to absorb the THz radiation; this is guaranteed for superconducting film devices into the visible range due to the very short momentum scattering times (note that any superconducting portions of the devices also absorb THz radiation); and on b) being able to change their resistance as the electrons heat. These two properties do not depend on the frequency, once the frequency is above the bandgap frequency.
3) The majority of HEB receivers now use quasi-optical coupling. Some HEB receivers in the range up to maybe 2.5 THz are likely to be waveguide-coupled in the next few years. The highest THz frequencies are likely to continue to use quasi-optical coupling. Antennas can in principle be efficient (good radiation patterns, low ohmic losses) up to at least 30 THz, but *fabrication will be a greater challenge at the highest frequencies*.
4) A related challenge is that of providing the LO power: The "lower" THz range is likely to see broader use of multiplier LO sources, as these continue to improve. In the higher THz range laser sources will likely continue to dominate. Quantum Cascade Solid state lasers (QCLs) have had a breakthrough recently (see paper by Quing Hu et al, this symposium [7]; also Semenov et al [8] reported using a QCL to pump an HEB mixer at 4.3 THz). Realistic values of the LO power required for typical PHEBs at the dewar window are from 0.5 μW to a few μW.

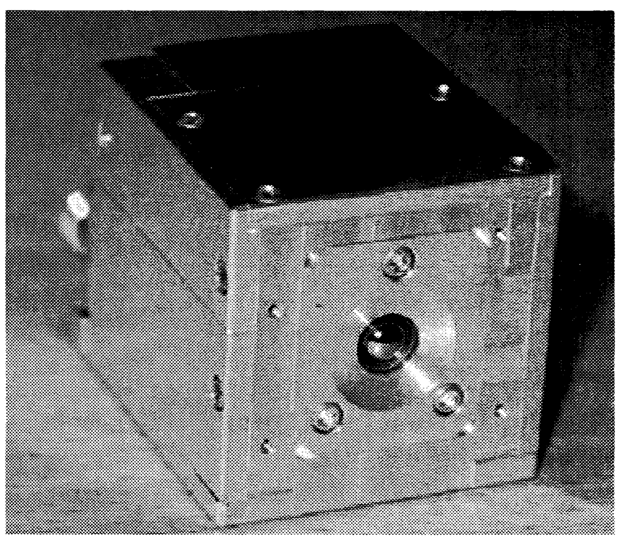

Figure 3. One of the HEB mixer blocks for HIFI

5) There are missions planned which need heterodyne detectors in the highest THz area, which are in the long-term planning stage, such as SAFIR [9].

II. BASIC QUESTIONS ABOUT HEBs

1) Optimum HEB material/cooling?

There is at least a temporary, practially motivated, answer to the question about which is the optimum HEB material, and which is the optimum cooling method (DHEB or PHEB): The systems which have been brought to fruition and have been installed on telescopes all use PHEBs. Also, the majority of all laboratory measurements in Figure 2 are for PHEBs. Laboratories which have tried both types, such as SRON, have achieved their lowest receiver NTs with PHEBs. This is not to say that the situation may not change. The DHEBs all use lower T_c materials, which according to theory should have lower output noise. If we examine the equation for the noise temperature of an HEB mixer, we can discern why the DHEBs may not prevail despite this advantage:

$$T_{R,DSB}=(L_c/2)(T_{FL}+T_J+T_{IF}) \qquad (1)$$

Here, the temperature fluctuation term, T_{FL}, which is proportional to T_c^2, tends to dominate. THz DHEBs tend to have larger conversion loss, however, which explains why PHEBs still have a lower (or similar) receiver NT. DHEBs tend to require less LO power, but are also much more sensitive to being biased at the exact optimum point, which is a practical disadvantage. Among PHEB materials, NbN has dominated for a while, although NbTiN may also compete, see several papers at this symposium.

2) HEB Models are as Good and Precise as those for SIS Receivers?

The answer to this question is unfortunately an emphatic NO at the moment. Here lies a major challenge for HEB researchers in the next few years. The program to accomplish this might proceed as follows: Step 1: Empirical models based on a variety of measured data; Step 2: Physical models will allow improved performance; Some suggestions based on our projects at UMass follow below.

3) New types of measurements to perform.

a) Impedance measurements with THz LO applied. This type of measurement has not been performed until recently. See Fernando Rodiguez-Morales's poster paper [10] at this symposium for some fresh results, one of which is shown below.

All *gain bandwidth* measurements of HEB devices have so far been performed at typical frequencies of 600 GHz. This is either below or barely above the superconducting bandgap frequency under typical operating conditions, and it is important to check what the gain bandwidth with actual THz LO applied is. An impedance measurement should be able to accomplish this, and also show any potential dependence on the LO frequency.
b) Receiver noise bandwidth measurements. There are still only a few measurements on the actual *receiver noise temperature bandwidth* (the IF bandwidth at which the receiver noise temperature becomes twice that at the lowest IF frequencies). It is predicted to be

about twice the gain bandwidth (i.e. 5 GHz to 7 GHz for NbN PHEBs) which has been verified in measurements at CUT and at UMass [10]. The UMass measurement demonstrated the use of a broadband MMIC IF amplifier for this test, see below:

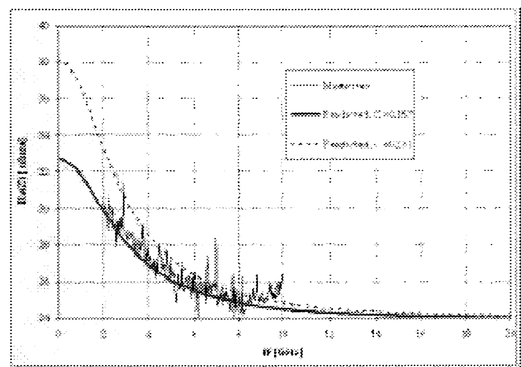

Figure 4. Measured IF impedance (real part) for an HEB device, vs frequency [10].

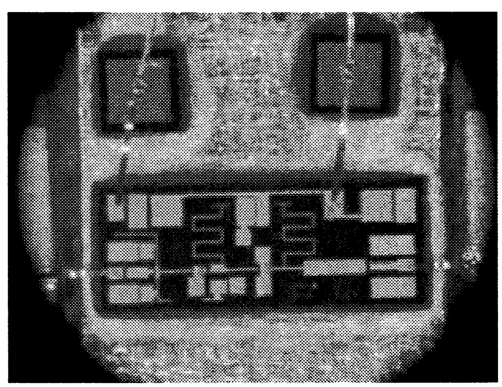

Figure 5.Broadband InP MMIC LNA used at UMass/Amherst (Courtesy of Dr. Sander Weinreb).

The *gain bandwidth* can also be measured at THz frequencies by employing a tunable THz sideband source. We are performing such measurements in collaboration with UMass/Lowell.

4) What is the effect of Quantum Noise on THz HEB mixers?

The author and Erik Kollberg of CUT began to tackle this unsolved question in a paper given at the previous ISSTT [11]. The main point is to use the Callen-Welton noise power expression for all components, including the HEB. A complication arises from the fact that all of the HEB absorbs THz radiation, while only a part of it is actually producing IF power. We have developed a simplified model to take this effect into account, but further detailed work will need to go hand in hand with the development of physical hotspot models for the HEB (see below). A preliminary (unpublished) result is shown in Figure 6 below. We used data measured (crosses) by the DLR group [12], and also included their estimates of the optical input losses. We used the ratio of the resistances of the active and passive parts of the HEB, respectively, as an adjustable parame ter. Although our calculations then fit the measured data, it is much too early to judge the correctness of the theory. Further measurements and theoretical investigations are ongoing.

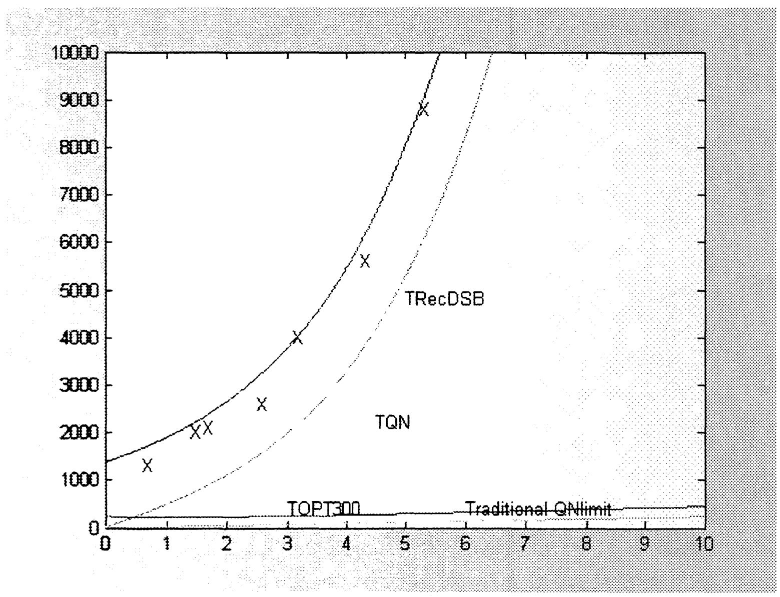

Figure 6. Calculated and measured DSB receiver NT for HEBs as a function of LO frequency.

5) Physical HEB Models – Hot Spots!

Erik Kollberg and I termed the type of model which has been used by essentially all HEB researchers since the beginning of the field of HEB mixers, the "standard model", in reference to the standard model used by high energy particle physicists. Like the high energy physics standard model, it forms a consistent frame work against which to compare our measured data. In both fields, the standard models are known to be an incomplete picture of reality. We showed in a paper at the 10^{th} ISSTT [12] that one can use adjustable parameters in the standard model to achieve good agreement with measurements for the variation of conversion loss, output noise, and receiver noise temperature, as a function of the LO power (or bias current, which is the same thing). However, the variation of those same quantities with bias voltage disagrees drastically with the standard model. So, everybody has realized that hot spot models make a bt more sense.

After much excellent work by several people, there is still no accepted hot spot model (for good review of some earlier work, see e.g. [12,13]). Again, a combination of careful measurements and theoretical work is expected to eventually solve this problem.

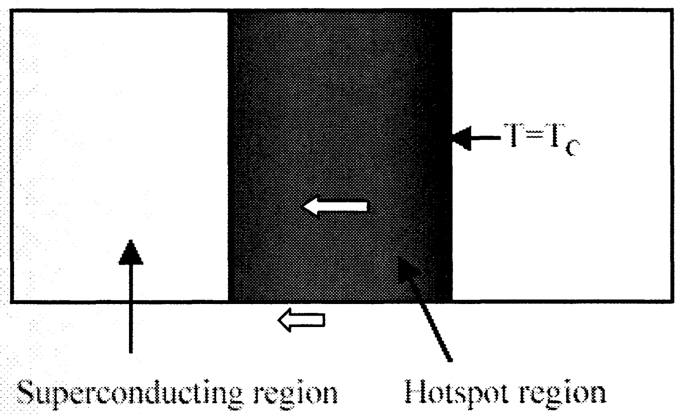

Figure 7. A hot spot model.

Much of the controversy has been centered on which parts of the HEB (see Figure 7) that actually produce an IF resistance (and thus voltage) in response to THz power. In a simplified picture of the hotspot, the inside of the hotspot is already in the normal state, and thus can not change its resistance. On the other hand, the SC regions outside the hot spot obviously can not change their resistance either. Which leaves the boundaries of the hotspot! Recent work by Harald Merkel et al. indicates that the active regions may spread further away from the actual boundaries than one would deduce from the simplified picture described above [14]. Some of the important features which have been recently added to the hotspot models are

a) Since THz radition is absorbed in the entire HEB, but only parts of it contribute to the conversion gain, there must some loss in conversion gain compared with the standard model – this agrees with for example [12].

b) Andreev Reflection (AR) of the electrons at the SC/hotspot boundary (also in [13]).

c) A model for the very slow expansion/contraction of hot spots in the *unstable ("bistable")* portion of the IV-curves [15], including AR..

d) The models will now also need to explain the remarkable findings of the SRON group that devices with *higher* normal resistance have *lower* NT [16].

6) Are Superconducting HEBs all there is?

We should not forget that there are competing HEB or other types of devices which do not use SC films! Note the IF bandwidth record of 40 Ghz set by Mark Lee et al [17] with a "ballistic" 2DEG mixer! This receiver may have difficulties in reaching all the way to the actual THz range due to charge-carrier inertia, though. Mark Sherwin's TACIT detector [18] is resonant and would not have that problem. These devices, and Al Betz's photoconductive HgCdTe mixers [19] are all worth watching.

III. CONCLUSION

Finally, I want to re-emphasize what is maybe the most important challenge for THz HEB researchers – how do we expand the frequency range of very low noise HEB mixers all the way to 30 THz? If we draw a receiver noise temperature diagram with a wider frequency scale as in Figure 8, then we see better what we are up against! Note that the photoconductive mixers at 30 THz (10 μm) reached close to the quantum noise limit long time ago, and that the Erbium-doped fiber amplifiers (they are masers!) are right on that limit at 1.5 μm wavelength. We have some work still remaining ahead of us!

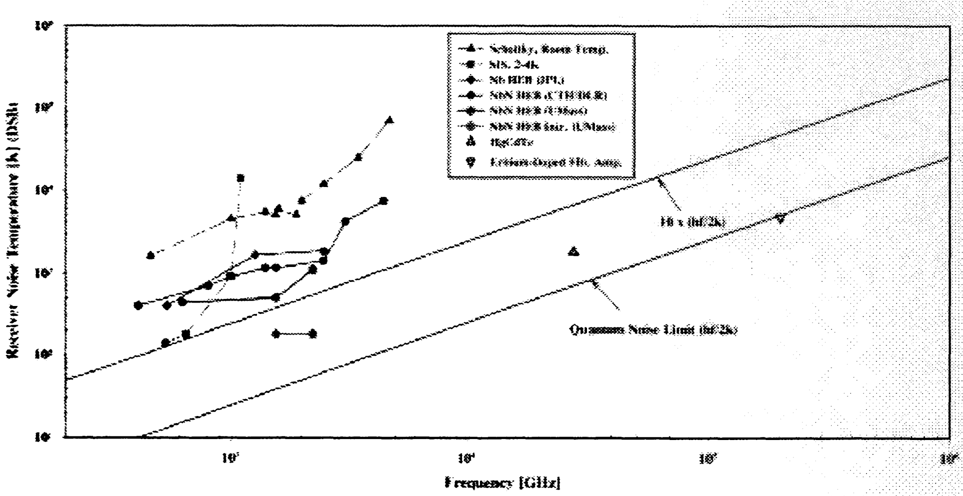

Figure 8. Receiver NT for different devices over a wide frequency range.

IV. ACKNOWLEDGEMENTS

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