New results on THz HEB low-noise receivers and focal plane arrays

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ABSTRACT

HEB technology continues to extend the state-of-the-art for THz low-noise receivers. This talk discusses recent measured noise temperatures for NbN HEB receivers from which we infer intrinsic noise temperatures which approach the quantum noise limit within a factor of 3-5. We discuss the feasibility of achieving noise temperatures even close to the quantum limit noting that this limit has been reached both at lower frequencies (SIS mixers) and at higher frequencies (Erbium-doped fiber amplifiers and HgCdTe mixers in the near IR). Another approach for considerably enhancing the speed with which THz receivers collect data is to employ a focal plane array system. We will discuss our design approach and general constraints for such a system.

Keywords: THz frequencies, heterodyne detectors, quantum noise limit, superconducting devices, hot electron bolometers, focal plane arrays, integrated receivers

1. INTRODUCTION

At the previous SPIE Annual Meeting, we described our work and results on low-noise THz receivers which utilize the new Hot Electron Bolometric (HEB) technology. Specifically, we have developed such receivers with devices fabricated from thin (3.5 - 4 nm) NbN films. In the present paper we report on new results for this approach, including new work and ideas for focal plane arrays of HEB receiver elements. In the spirit of the topic of this SPIE conference, “Terahertz and Gigahertz Photonics”, we will also put these devices and receivers into the context of the entire frequency range from GHz to the optical.

The development of low-noise receivers in the THz frequency region is primarily motivated by the need for low noise and low power consumption receivers for the next generation of space-based and airborne astronomical observatories (FIRST, SOFIA, etc.), as well as space-based remote sensing of the Earth’s atmosphere (EOS-MLS). Figure 1 surveys the state-of-the-art of the sensitivity of coherent receivers from 300 GHz to 300 THz. The maturity of the technology in a particular frequency region may be measured by how close it is to reaching the fundamental noise temperature limit which is set by quantum mechanics and the Heisenberg uncertainty relation, the “quantum noise limit”. This noise temperature is equal to $hf/2k$, where $h$ is Planck’s constant and $k$ is the Boltzmann’s constant. The interpretation of the quantum noise limit concept, and even the definition of receiver noise temperature ($T_{\text{rx}}$), has to be considered carefully in order to be consistent with this high frequency range.

We will discuss this topic in the next section. We can already see from the comparison in Figure 1, however, that the quantum noise limit is being approached by SIS receivers at frequencies of a few hundred GHz. In the other extreme of the frequency region covered, Erbium-doped fiber amplifiers are even closer to being ideal quantum-noise limited detectors with a noise temperature of 4,800 K, essentially equal to $hf/2k$, at a frequency of 200 THz (1.5 μm wavelength). They fall low in that sense the tra-
dition of early quantum electronic devices in the GHz range, i.e. traveling-wave masers, which were also essentially right at the quantum noise limit.\(^4\)\(^,\)\(^5\) Heterodyne (mixer) receivers which use \HgCdTe\ devices and \CO\ lasers as LO sources, have achieved \(T_{\text{rx}} = 1.800\, \text{K}\) at about 28 THz (10.6 \(\mu\)m) or 3 \(\times\) \(\hbar\omega/2k\)\(^6\). Until a few years ago, the main heterodyne receivers available for the THz region utilized nonlinear frequency-conversion in either GaAs Schottky Barrier Diodes (SBD) or InSb Hot Electron Bolometers (HEB). THz SBD mixer technology has recently made a transition from cumbersome whiskered diodes in corner-cube mounts to planar versions in waveguide\(^7\). The Double Side Band (DSB) receiver noise temperature of SBD mixer receivers has remained essentially stationary at about 100-200 \(\times\) \(\hbar\omega/2k\), much larger than at either end of the spectrum we defined above (and the noise temperature of SBD receivers increases to 70,000 K at 4.75 THz, or 600 \(\times\) \(\hbar\omega/2k\)\(^8\)). Fabrication technology and material parameters limit the size of the monolithic junction and therefore limit the noise temperature for performance. In addition, SBD receivers require a few mW of LO power. InSb mixers have always been too restricted in bandwidth (only about 1 MHz) for most applications. The excellent noise performance of SIS mixer receivers is limited to frequencies below or about equal to the superconducting bandgap frequency, which is 700 GHz for the presently prevalent Nb devices. There has thus been a long-standing gap in frequency from 1 THz to close to 30 THz, in which the sensitivity of heterodyne detectors is at least two or orders of magnitude worse than the quantum limit.

Hot Electron Bolometric (HEB) mixers, which use nonlinear heating effects in superconductors near their transition temperature, have become an excellent alternative for applications requiring low noise temperatures at frequencies from 1 THz up to the NIR, and thus promise to fill in the gap in near-quantum noise limited sensitivity between 1 THz and 30 THz. There are two types of superconducting HEB devices, the Phonon-Cooled (PC) version\(^9\), and the Diffusion-Cooled (DC) version\(^10,11\). At present, the lowest recorded receiver noise temperatures above 1 THz have been obtained with the PC type HEB\(^1,12,13,14,15,16\), although the difference is not very large (see Figure 1). At 1.56 and 2.24 THz the best receiver noise temperatures are 500 K (13 \(\times\) \(\hbar\omega/2k\)) and 1,100 K (20 \(\times\) \(\hbar\omega/2k\)), respectively\(^1,13,14\). At 5.3 THz, the best performance at present is 8,800 K\(^16\) (71 \(\times\) \(\hbar\omega/2k\)). As

![Figure 1. Noise temperatures as a function of frequency (300 GHz - 300 THz) for state-of-the-art receivers.](image-url)
in our earlier paper, we will only describe the PC HEB here. Super conducting HEB mixers also require much less LO power than SBD receivers (100nW to 1µW for PC HEBs presently). The only practical LO source, presently available, is an FIR gas laser although solid state LO sources with sufficient amount of power are under development and will be available in the future.

2. THE QUANTUM NOISE LIMIT AND THE ROLE OF ZERO-POINT FLUCTUATIONS

This section will review the definitions we are using in our work for black-body radiation power and receiver noise temperature, and how the latter is derived from the measured Y-factor. We are following the definitions proposed by Kerr.$^{2}$

2.1. Blackbody radiation law

It has been customary among engineers and scientists working at GHz frequencies to use the approximate Rayleigh-Jeans law for the amount of available noise power per hertz bandwidth from a passive resistor at temperature $T$

$$P \approx \frac{kT}{\exp\left(\frac{h\nu}{kT}\right)-1}$$

The above expression is an approximation for the Planck formula, valid when $h\nu \ll kT$:

$$P_{\text{Planck}} = kT \left[\frac{h\nu}{kT} \right] \left[\frac{\exp\left(\frac{h\nu}{kT}\right)-1}{\exp\left(\frac{h\nu}{kT}\right)}\right]$$

Callen and Welton$^{17}$ showed, however, that a zero-point vacuum fluctuation term has to be added to correctly describe the noise from a resistor:

$$P_{\text{C&W}} = kT \left[\frac{h\nu}{kT} \right] \left[\frac{\exp\left(\frac{h\nu}{kT}\right)-1}{\exp\left(\frac{h\nu}{kT}\right)}\right] + \frac{h\nu}{2}$$

Eq. (1) to Eq. (3) give very close values for the case $h\nu \ll kT$ but begin to differ in the THz region, typically at about 2 THz. It then becomes important to include the extra term $h\nu/2$ in the input noise to any receiver. This definition is now used by all workers on HEB THz mixers.

2.2. Noise temperature

The receiver noise temperature is most conveniently defined as,

$$T_{\text{RX}} = \frac{P_{\text{C&W}}}{k}$$

where $P_{\text{C&W}}$ is assumed to exist at the input of the receiver.
2.3. Y-factor

If the Y-factor is measured in the conventional manner by inserting matched loads (absorber material) in front of the receiver, then the receiver noise temperature can be related to the Y-factor through,

\[ T_{RX} = T_{C&W}^{hot} - \frac{YT_{C&W}^{cold}}{Y - 1} \]  

(5)

2.4. The optical regime

In the optical regime, i.e. \( hf > kT \), Eq. (3) becomes almost entirely \( hf/2 \). The entire power output from a matched load at these frequencies thus consists of the zero-point vacuum fluctuations. These still give rise to a noise output for a receiver.

2.5. The quantum noise limit

As discussed in ref. 18, the minimum noise output per Hz bandwidth for a mixer receiver is \( hf \), referred to one sideband at the receiver input. For a double-sideband (DSB) receiver being used for wideband measurements, the minimum total noise temperature of a mixer receiver system is \( hf/2k \). This is the form of the quantum noise limit we will use. Note that the limiting noise temperature will be \( hf/2k \) for both the Erbium-doped amplifier and the HgCdTe mixer in Figure 1. The amplifier has a minimum noise output corresponding to \( hf \) at the input (use Eq. (3) for \( hf > kT \)). Half of this noise power arises from the zero point fluctuations at the input of the amplifier and the other half from the amplifier itself (it has a noise figure of 3 dB). The amplifier noise temperature is thus \( hf/2k \). If we compare DSB mixers and quantum electronics amplifiers in Figure 1, we can use the same quantum noise limit.

3. DEVICE FABRICATION AND RECEIVER DESIGN

The device design and fabrication were described in detail in last year’s paper and we will only review these briefly here, and mention some new findings. Our HEB devices are made from a thin (3.5 to 4 nm) film of NbN deposited on a substrate of silicon by DC magnetron sputtering. Thinner films are desirable in order to achieve wider IF bandwidth. The critical temperature of the NbN film is about 10 K depending on film quality and thickness, and efficient mixing occurs at about half that temperature. Much effort has been spent on improving the quality of the NbN films, which is especially critical for the thin-film devices. This effort is still ongoing. The critical current of a device is a few hundred \( \mu \)A, while a typical DC bias voltage is 1 mV. Since the device acts as a bolometer, the absorbed LO power, which is a function of the device area, is measured by the device itself and is computed from its I-V curve. Our devices have a length of 0.6 to 1 \( \mu \)m, a width of 5 \( \mu \)m, and require LO power from 0.5 to 1 \( \mu \)W.

We couple our devices quasi-optically through a 4 mm diameter elliptical lens made from high-purity silicon. In order to facilitate testing over a wider range of frequencies, we have initially used a log-periodic complementary toothed antenna, see Figure 2. We have used a log-periodic antenna with a maximum frequency of 3.4 THz. Our log-periodic antennas have a 4:1 bandwidth. The antenna is fabricated from a gold film using lift-off lithography. At the moment, we use no reflection matching for the silicon lens (\( \epsilon_r = \) 11.8). A recent advance is that we have shown that parylene is a very good material for this matching layer. 16, 19

The HEB receiver is cooled in an IRLAB liquid helium dewar, and THz radiation enters the dewar through a 0.75 mm thick polyethylene window. The mixer is connected through a bias tee and a semi-rigid coaxial cable to a cooled HEMT IF amplifier. In the most recent experiments, the IF chain noise temperature was estimated to be 7 K with a bandwidth from 1250 MHz to 1750 MHz.
The LO source was an ultra-stable CO$_2$-laser pumped difluoromethane gas laser, which could be made to lase either at 191 $\mu$m wavelength (1.56 THz) or at 134 $\mu$m (2.24 THz) by choosing one of two orthogonal polarizations. A 6 $\mu$m thick mylar sheet was used as beam splitter, and a dielectric lens was used to focus the laser LO. The 50-100 mW output power of the laser was attenuated by crossed wire grid polarizers in order to set the optimum LO level. The IF output power was detected on a power meter and recorded on a computer with the help of a Labview program.

4. EXPERIMENTAL RESULTS FOR SINGLE-ELEMENT RECEIVERS

4.1 Noise temperature and optical losses

Table 1 gives a summary of data measured for our best device, which reached DSB noise temperatures at 1.56 THz of 500 K and at 2.24 THz as low as 1,100 K. The same device was measured at both frequencies within minutes without altering the receiver configuration except for changing the laser frequency. The output noise temperature was measured by comparing the total output noise power in the optimum operating point (with LO applied) with that of the device in the superconducting state (the bias voltage was decreased to zero). Since the IF noise temperature was known, we could find the output noise temperature ($T_{\text{out}}$) from this measurement. The optical coupling loss was estimated from known losses in windows, lens reflection loss, etc. The remaining conversion loss is the intrinsic conversion loss, $L_{\text{c,i}}$. A set of consistent values of $L_{\text{c,i}}$, $T_{\text{out}}$, and $T_{\text{R,DSB}}$ can then be obtained. We have identified part of the increase (0.5 dB) in optical losses from 1.56 THz to 2.24 THz as being due to a resonance in the polyethylene window material. Also, the atmospheric attenuation is higher at 2.24 THz than at 1.56 THz. The thermal noise power from the cold source had a path length of about 0.6 m before it reached the dewar window and the estimated attenuation over this path at 2.24 THz is 0.5 - 1 dB. There is still an unexplained increase of about 2 dB. Some of the increases in optical losses are inevitable but careful optical design should be able to eliminate at least part of this increase in loss with frequency.

We now know that it is possible to decrease the optical loss, and thus the receiver noise temperature by 30% by using a parylene matching layer. We have noted the predicted performance with this matching layer in Table 1.
4.2 Intrinsic receiver noise temperature and the quantum noise limit

The intrinsic receiver noise temperature at 1.56 THz is 180 K. To arrive at this estimate, we needed to know the value of the optical loss (5 dB), and this estimate may have some errors probably not larger than 1-2 dB, however. We also ascribe the increase in noise temperature from 1.56 THz to 2.24 THz entirely to the increased optical loss. The rationale for this is that all present HEB mixer models assume that the intrinsic conversion loss is independent of RF frequency as long as the frequency is higher than the superconducting bandgap frequency (about 0.8-1 THz for our films). Some of the increase in optical loss may be due to a concentration of the THz currents in the device toward the edges, as described in ref. 16.

Within these uncertainties, we can estimate that the intrinsic receiver noise temperature then is equivalent to 5 x hf/2k at 1.56 THz, and 3.3 x hf/2k at 2.24 THz. These sensitivities are as close to the quantum noise limit as is typically obtained for SIS mixers. Their magnitude also agrees with the best models presently available for PC HEBs20. These models are not yet sufficiently accurate, however, and cannot predict the values of all experimentally measurable parameters correctly. An important remaining question is the distribution of the current through the device as mentioned above. Work is still on-going to resolve these questions, which must be anwered before we know how close to the quantum noise limit present HEBs can reach. Future experiments should also attempt to measure the noise temperature at a close as possible to the device in order to enable more accurate modeling of the HEB. One should note that it is not clear whether the present quantum noise theory for mixers, which has been worked out in detail for SIS mixers21, for example, applies to the HEB case.

4.3 New results on HEB bandwidth

The IF bandwidth of our devices made from 3.5 to 4 nm of NbN on silicon is typically 3 GHz13. This is the 3 dB bandwidth of the conversion loss (B_G), while the more important property for applications is the receiver noise bandwidth, B_N, the frequency at which the noise temperature per a turn has increased by a factor of two compared to the value for thermal fluctuations (the minimum value occurs at very low IF frequencies). The ratio B_N / B_G is about two to three, and is greater the larger the thermal fluctuation noise is compared to other noise terms (Johnson noise and IF amplifier noise). Since the fluctuation noise is usually large in the receiver we report here, we estimate that the receiver noise bandwidth is at least 6 GHz.

New results which demonstrate this validity for B_G have also been obtained in collaboration with Chalmers University15. In this work we used NbN films on MgO substrates, which yield higher phonon transmission from the NbN film. B_G as high as 4.8 GHz was obtained, and the receiver noise bandwidth is estimated to be 10 GHz or greater. It was shown that it is very important to minimize the parasitics in the device mount in order to achieve the maximum IF bandwidth in practice.

5. FOCAL PLANE ARRAYS WITH INTEGRATED HEB RECEIVERS

In order to fully utilize the future space-borne and airborne facilities, it will be advantageous to develop Focal Plane Arrays (FPAs) which incorporate the new low-noise HEB receivers. In astronomical THz observations, for example, one often wants...
to map an area such as an interstellar cloud or a galaxy. The speed with which this mapping can be done will increase in proportion to the number of elements in the array. Such systems exist at millimeter waves in ground-based telescopes\textsuperscript{22,23}. There are well-known limitations for the smallest beam spacings which can be obtained\textsuperscript{24}. These can be discussed in terms of the geometric spacing ($\Delta x$) of adjacent elements in the array. If each element in the array illuminates a telescope at an f-number of $f/D$, then ideal sampling of the focal plane image at the Nyquist rate requires that $\Delta x = 0.5 x (f\lambda/D)$\textsuperscript{23,25}. There is no type of feed element which is capable of being spaced this close while still illuminating the telescope efficiently\textsuperscript{22,26}. About the best which has been achieved in practice is $\Delta x = 1x(f\lambda/D)$. Corrugated horns, for example, which are very efficient feed antennas, must be spaced at about $2x(f\lambda/D)$\textsuperscript{22}. The displacement ($N$) of the telescope beam on the sky, measured in Full Width Half Maximum (FWHM) beamwidth is also related to $\Delta x$ as $N = \Delta x/1.2\lambda(f/D)$\textsuperscript{24}. A narrow array element spacing of about $1.2x(f\lambda/D)$ corresponds to a spacing of adjacent beams on the sky of one FWHM beamwidth.

There are two different methods for coupling dielectric lenses to an antenna array:

(i) a single-lens configuration; and
(ii) a multi-lens configuration.

If we first consider the single-lens case, the individual elements placed near the focus of the lens will radiate a beam which has an f-number of roughly 1.0, i.e. a 56 degree FWHM beamwidth. Filipovic et al.\textsuperscript{27} analyzed this case and derived the minimum spacing possible. To obtain a rough estimate, we assume a spacing corresponding to one beamwidth and find $\Delta x = \lambda/\sqrt{\varepsilon_r}$, or $35 \mu m$ for $\lambda_0 = 119 \mu m$. This leads to very tight constraints on any wiring which has to be connected to the devices and antennas, and it is obviously impossible to place the IF amplifiers close to the antennas.

The multi-lens configuration, on the other hand, is much more flexible. The relatively small (radius $R = 10 \lambda_0$) elliptical lens, which we have developed, lends itself well for use in this "fly's eye" type of array, see Figure 3. Both the LO and the in-

![Figure 3. A portion of an HEB focal plane array with a twin-slot antenna element.](image-url)
coming signal are injected through a quasi-optical diplexer. The optics thus are unchanged from our single-element approach. The beamwidth from each lens is approximately given by $1.2 \times \lambda/(2R)$, and the lenses can be placed at a spacing equal to their diameter ($2R$), i.e. $\Delta x = 2R$. The f-number of the array elements will be approximately $2R/\lambda (\approx 20)$, which may be about right for a typical Cassegrain telescope with no recourse to further focusing. The beam-scan ($N$) will be about one FWHM beamwidth. The angular resolution (angular spacing between adjacent pixels) will thus be about equal to the diffraction-limited beamwidth of the telescope which is typically of the best resolution obtainable for FPA receivers as discussed above.

The FPA cannot use the log-periodic toothed antennas which we have employed so far since these are unnecessarily large. The focal plane array system is also not likely to require the very wide bandwidth of these antennas. We instead propose a twin-slot antenna as shown in Figure 3 or a slot-ring antenna as shown in Figure 4. We have shown that the twin-slot antenna yields the same noise temperature at 600 GHz when coupled to an NbN HEB device in collaboration with Chalmers University.

The slot-ring antenna has been demonstrated in a four-element array for a 35 GHz monopulse radar and also, for example, in 94 GHz MMIC receivers. Both of these antennas are linearly polarized and the slot ring can receive radiation in either of two perpendicular polarizations. There are several possible configurations to explore for the slot ring version. Figure 5 shows one such configuration in which the LO and RF are injected in the same polarization, as in our present single lens receiver. The IF is extracted through a coplanar waveguide (CPW) from the point on the ring at which the THz fields have a null. It is important to use air bridges in order to cancel the even mode on the CPW. In the above-mentioned monopulse radar project, the LO and signal were injected in orthogonal polarizations through a simple wire grid, and two (reversed) Schottky barrier mixer diodes were placed at the 45 degree positions across the ring, thus forming a balanced mixer. HEB devices cannot be reversed, as can Schottky diodes, but one or two devices could be placed at the 45 degree positions and this would allow very efficient LO injection (ideally with no loss) through a wire grid. The signal would also be injected with outloss, ideally. The RF impedance of the HEB device(s) would be adjusted in the usual way by varying its (their) aspect ratio for optimum coupling to the ring. Different types of filters can be implemented on the IF line in order to prevent leakage of the RF and LO through the CPW. Figures 5 and 6 show different versions of slot-ring antennas.

The entire silicon chip with antennas and NbN mixer devices would be fabricated in one process. MMIC HEMT amplifier chips (size about 1 mm$^2$) would be integrated with the mixer chips by etching them in a substrate, and transmission lines could be routed on a thin layer of spun-on dielectric. We have demonstrated similar structures in other work at UMass/Amherst. A wideband MMIC amplifier is under development in collaboration with Chalmers University of Technology (courtesy of Herbert Zirath). The amplifier will include on-chip impedance matching as well as bias circuitry for the HEB devices. A nominal bandwidth of 4-8 GHz will be suitable for many anticipated system applications. Another important consideration is to minimize the DC power consumption of the MMIC amplifier, and heating of the HEB device due to IF amplifier power dissipation.

**Figure 4.** A portion of an HEB focal plane array with a slotting antenna element.
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REFERENCES


