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# Low Noise Receivers Based on Superconducting Niobium Nitride Hot Electron Bolometer Mixers from 0.65 to 3.1 Terahertz

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**SUMMARY** Low noise terahertz (THz) receivers based on superconducting niobium nitride (NbN) hot electron bolometer (HEB) mixers have been designed, fabricated and measured for applications in astronomy and cosmology. The NbN HEB mixer consists of a planar antenna and an NbN bridge connecting across the antenna's inner terminals on a high-resistivity Si substrate. To eliminate the influence of direct detection and instability of the local oscillation (LO) power, a wire grid has been used to change the input LO power for compensating the shift of bias current during Y-factor measurement. The double sideband (DSB) receiver noise temperatures at 4.2 K without corrections have been measured from 0.65 to 3.1 THz. The excess quantum noise factor $\beta$ of about 4 has been obtained, which agrees well with the calculated value. Allan variance of the HEB has been characterized, and Allan time $T_A$ longer than 0.4 s is obtained. We also estimated the temperature resolution of the HEB from the Allan variance and obtained the minimum temperature resolution of 1.1 K using a Gunn oscillator with its multipliers at 0.65 THz as an LO source.

***key words:*** *hot electron bolometer (HEB), superconducting heterodyne mixer, terahertz (THz), receiver noise temperature*

## 1. Introduction

Heterodyne mixers based on hot electron bolometers (HEBs) combine excellent noise performance and lower local oscillator (LO) power requirment at terahertz (THz) waveband. Below 1.4 THz, Superconductor-Insulator- Superconductor (SIS) mixers exhibit noise temperatures quite close to the quantum limit $T_Q$=h$f$/k$_B$ (where h is the Planck constant, k$_B$ is the Boltzmann constant and $f$ is the operating frequency) [1], [2]. While for operating frequencies higher than 1.4 THz, SIS mixers are not working well due to their gap-frequency limitation and superconducting HEB heterodyne mixers have higher sensitivity and require less LO power [3]–[8]. This makes the HEBs highly attractive for both ground-based and space-based telescopes for astronomy [9]. The Herschel-HIFI used the HEB receivers with the noise temperature lower than $10 \times hf/k_B$ at $f = 1.41 - 1.92$ THz [10]. It can be expected that HEB mixers will be used widely at THz waveband in the near future. Here, we report the fabrication and properties of low noise receivers based on niobium nitride (NbN) HEB mixers at THz frequency waveband.

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## 2. Experimental

### 2.1 Mixer Chip

In the fabrication of mixer chip, NbN thin film is first deposited on a high-resistivity Si substrate by DC magnetron sputtering in Ar+$N_2$ gas mixture at room temperature (RT) [11]. From the atomic force microscopy (AFM) image of a 4.5 nm thick NbN film sample on Si substrate, a root-mean-square (RMS) roughness of about 0.42 nm is obtained over an area of 5 $\mu$m square. Its critical temperature ($T_c$) of about 9 K and critical current density of about $1.5 \times 10^6$ A/cm$^2$ at 4.2 K were obtained for such ultra-thin films. Then the NbN film is covered by photoresist. And two square openings are positioned on the photoresist by electron beam lithography. An additional NbN film of about 10 nm thickness is deposited, which is used as a buffer to keep the superconductivity of the bridge not being seriously degraded by the gold contact [7]. After that, a gold film with thinkness of about 50 nm is deposited and then we use photolithography and reactive ion etching to keep the width of the bolometer bridge. The bridge is fabricated with the thickness of 4 nm, length of 0.4 $\mu$m and width of 3 $\mu$m. When a small bridge made of the NbN film is irradiated with THz photons, the electrons inside will be heated up and the energy will subsequently relax to the substrate through the electron-phonon interaction [3], [4]. Finally, a complementary logarithmic-spiral antenna made of gold was connected to the two poles. The outer diameter of the antenna should be larger than $\lambda_{0\,max}/4$ and inner diameter smaller than $\lambda_{0\,min}/20$, where $\lambda_{0\,max}$ and $\lambda_{0\,min}$ are the maximum and minimum wavelength in the free space, respectively [12]. The picture of the HEB mixer is showen in Fig. 1 and the frequency bandwidth of the antenna is 0.4–4 THz.

### 2.2 Receiver Configuration

In the experiments, we use a quasi-optical scheme in which the HEB mixer chip is glued to the center of hyper-hemispherical Si lens with or without anti-reflection (AR) coating on its surface. As shown in Fig. 2, the lens is thermally anchored to the 4.2 K plate of a liquid helium cryostat. DC bias and IF output signal were seperated by a bias-tee. The IF signal is amplified by a cryogenic low noise amplifier (LNA; noise temperature 12 K, gain 30 dB, frequency range 1.3–1.7 GHz) working at about 15 K and two ordinary

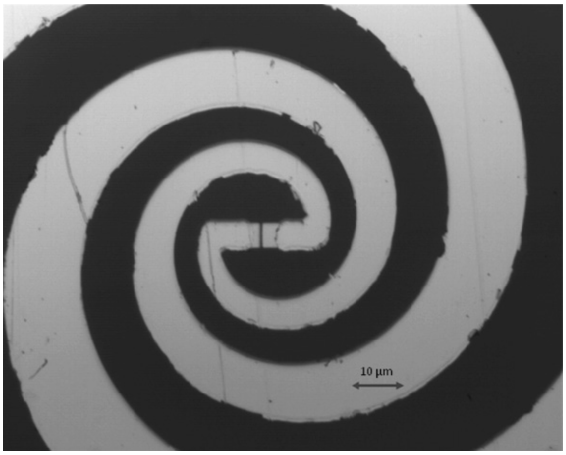


**Fig. 1** The photo of the HEB mixer.

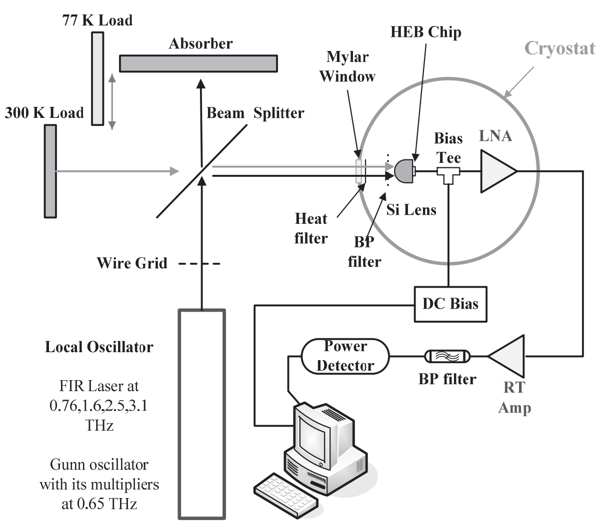


**Fig. 2** Schematics of the experimental setup.

RT amplifiers, with no additional isolator between the mixer and the amplifiers. It, then, went through an IF band pass (BP) filter with center frequency at 1.5 GHz and bandwidth about 100 MHz, and be collected by a microwave power detector, whose output can be read out by the voltage meter and recorded by a computer. The DC signal is controlled by a constant voltage bias circuit at RT. Using this circuit, the current and voltage signals of the HEB can be also recorded by the computer. We use an optically pumped far-infrared gas laser (FIRL 100 from Edinburgh Instruments Ltd.) at 0.76, 1.6, 2.5 and 3.1 THz or a Gunn oscillator with its multipliers at 0.65 THz as the LO sources. The receiver's double sideband (DSB) noise temperature ($T_N$) is measured by the Y-factor method using the equivalent temperatures of the blackbody loads at 300 K and 77 K, according to the Callen-Welton definition [13]. The loads are placed at about 30 cm far from the cryostat. A Mylar film with thickness of 15 $\mu$m is used for the beam splitter and the Mylar film with thickness of 36 $\mu$m is used for the cryostat window. The optical losses at 2.5 THz are calculated to be about 0.05 dB for the

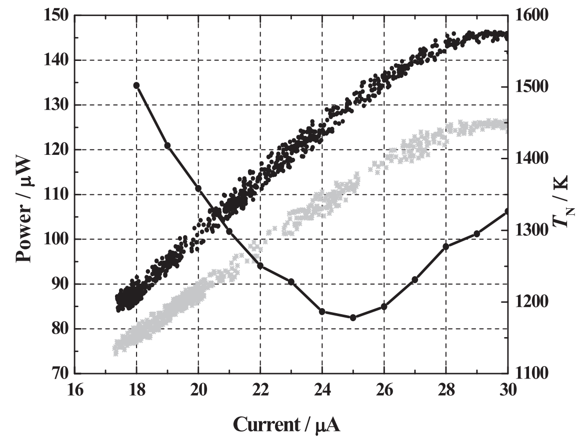


**Fig. 3** Smaller black points and gray points are IF output powers as a function of bias current at 300 K and 77 K. Black line connected with calculated values (larger black dots) is the noise temperature at different bias current for a constant bias voltage.

window and 1.2 dB for the beam splitter. To reduce the environment noise in our lab, all the equipments except the laser and computer are placed into an RF shielding room.

Because of the direct detection effect [8], the bias currents at some bias voltages can change up to 10 $\mu$A, when the temperature of the load changes between 300 K and 77 K. So we put a THz BP filter with about 10% bandwidth made by Virginia Diodes, Inc.(VDI) in the front of the Si lens at 4.2 K. But it seems not enough for this purpose, there is still about 5 $\mu$A change between 300 K and 77 K at some bias points. So a wire grid is employed at the same time to change the LO power compensating the shift of bias current during Y-factor measurement. In this way, the measurement will not be influenced by the direct detection effect and the instability of LO power. In details, we bias the bolometer to a constant voltage and use the wire grid to change the input LO power, so the bias current of the HEB will also be changed with the adjustment of the LO power. Then we record the IF output power at 300 K load as a function of the bias current. In the same way we record the IF output power and bias current again with 77 K load in front of the window. As shown in Fig. 3, black points are the bias current and IF output power with 300 K load, gray points are with 77 K load. In this way, we can use the IF output power of 300 K load and 77 K load at the same bias current to calculate the noise temperature by using the Y-factor method, and obtain the relationship between the $T_N$ and the bias current at this constant bias voltage. Finally, we change the bias voltage arround the optimized condition and measure the $T_N$ with different bias currents again to got the $T_N$ at different bias voltages. Because we change the LO power and record all the output of IF power and bias current when we are measuring the $T_N$ at a fixed bias voltage, the stability of the LO source will have no influence to get accurate $T_N$ for the bias voltage by this method.

## 3. Results and Discussions

### 3.1 Receiver Noise Temperature

The unpumped and optimally pumped (LO at 2.5 THz) *I-V* curves of an NbN HEB mixer working at 4.2 K with 2.5 THz AR coating are shown in Fig. 4(a), together with the DSB receiver noise temperatures ($T_N$) measured at different bias points. The $T_c$ of the HEB is about 8 K and transition width ($\Delta T$) is about 1.3 K. The critical current $I_C$ is 100 $\mu$A at 4.2 K and the normal state resistance $R$ is about 150 $\Omega$, which is 2 times higher than the calculated impedance of the log-spiral antenna. This impedence mismatching between the HEB mixer and the antenna leaves some room for further improvement of our receivers. The uncorrected $T_N$ reaches a lowest value of 1026 K. This value is about 8.56 times of the quantum limit $T_Q$=h$f$/k$_B$ at the frequency of 2.5 THz. At the optimized bias point with lowest $T_N$, the absorbed LO power is estimated to be about 130 nW, using the isothermal method [14]. To characterize the conversion loss of the HEB mixer, we use the U-factor method [15]. When the mixer is at the optimal bias point, the IF output power is 245 $\mu$W, and in the superconducting state (no bias and no LO), the IF output power is 24 $\mu$W. So the U-factor is about 10, and we know the noise temperature of the IF chain is 12 K, the measured $T_N$ of the HEB mixer is 1026 K. Then we obtain the $L_{total}$ at the optimal bias point is 12.0 dB from the equation $L_{total}$= 2(295+$T_N$)/U(4.2+$T_{IF}$). The calculated $L_{total}$ at different bias points around optimized condition are shown in Fig. 4(b).

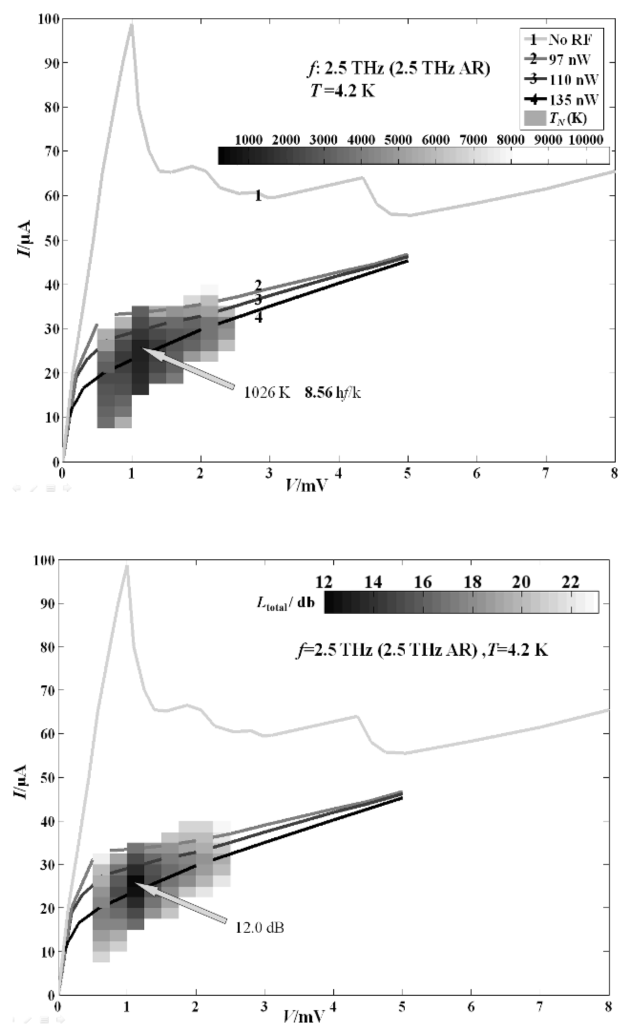


**Fig. 4** *I-V* curves without and with LO power, as well as DSB noise temperatures (a) and conversion losses (b) for different bias points. The receiver is glued on the Si lens with AR coating at 2.5 THz. 36-$\mu$m and 15-$\mu$m thick Mylar films are used as the window and beam splitter, respectively.

### 3.2 Excess Quantum Noise Factor

From the hot-spot theory [17], we know the electron temperature of the bolometer is higher than $T_C$ in the central section of the bridge, which is the "hot-spot," where we have low-frequency resistivity. Outside the hot spot, the low-frequency resistivity is zero. The hot-spot theory shows that the change of the low-frequency (DC and IF) resistance per unit length upon a change in the absorbed RF power is different in different sections along the bridge. So we divide the bolometer bridge (length $L$) into $N$ sections, each section has a length $\Delta x$=$L/N$. The DC resistance $R_{0n}$ depends on $x_n$ (e.g., $R_{0n}$=0 when $T_0 < T_c$). Obviously,

$$\sum_{n=1}^{N} R_{0n} = R_0 \equiv V_0/I_0 \tag{1}$$

where $V_0$ is the bias voltage and $I_0$ is the bias current. And we given

$$C_{0n}^{RF} = \left(\frac{\partial R}{\partial P_{RF}}\right)_n \Delta x; \quad C_{0n}^{DC} = \left(\frac{\partial R}{\partial P_{DC}}\right)_n \Delta x \tag{2}$$

as the change in resistance at the $n_{th}$ section for a small change in RF or DC power. Using the quantum noise theory [17], we know the excess quantum noise factor $\beta$ is an important value to estimate the contribution of quantum noise from the equation that $P_{QN}$ = h$fB\beta$, and $\beta$ can be calculated as

$$\beta = N \cdot \left[\sum_{1}^{N}\left(\frac{C_{0n}^{RF} I_0}{1 - C_{0n}^{DC} I_0^2}\right)^2\right] \cdot \left[\sum_{1}^{N}\left(\frac{C_{0n}^{RF} I_0}{1 - C_{0n}^{DC} I_0^2}\right)\right]^{-2} \tag{3}$$

So we need to know $C_{0n}^{RF}$ and $C_{0n}^{DC}$ in each section to calculate $\beta$.

To simplify this model, we first assume the change of resistance in dependencies of the DC and RF power for a very small signal power are equal in a small section, so $C_{0n}^{RF}$ =$C_{0n}^{DC}$ in each section, (the whole $C_0^{RF}$ and $C_0^{DC}$ are very different because the RF power are equal in each section but the DC power is mainly in the hot-spot sections where resistance are much bigger than other sections), we assume they are $C_{0n}$. Because the electron temperature at the edge of the hot spot is very close to $T_C$, so $C_{0n}$ at this region is much bigger than other regions on the bridge [18], [19]. We

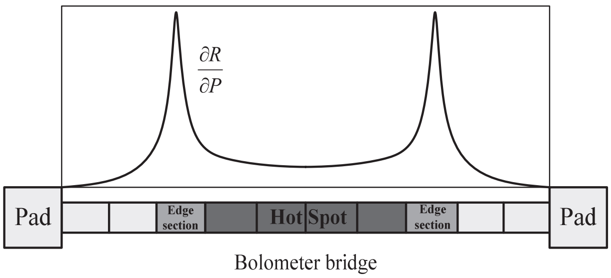


**Fig. 5** Illustration of the variation of $\partial R/\partial P$ along the bolometer bridge according to the hot-spot theories [18], [19].

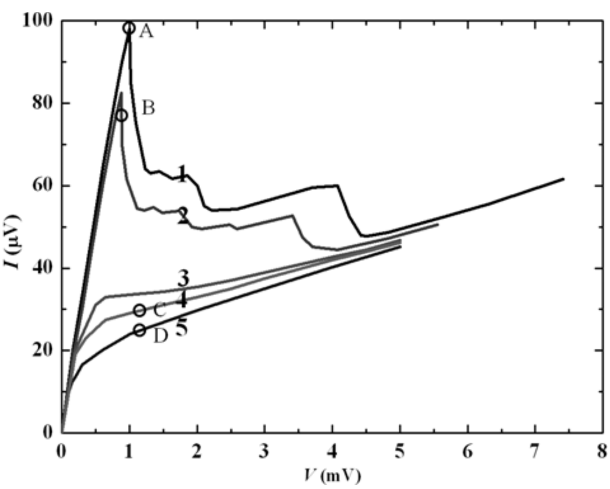


**Fig. 6** Curve 1 is *I-V* curve without LO, then we add a little LO power, we got curve 2. Curve 5 is the *I-V* curve at the optimized LO power and curves 3 and 4 are the *I-V* curves that decrease LO power a little from optimized LO power.

divide the bolometer bridge into 10 (0.4 $\mu$m the whole bridge length and thermal healing length is 40 nm) sections, two of which are the edge sections where the $\partial R/\partial P$ is much bigger than other sections, as shown in Fig. 5.

In the edge section, when we increase the input power, the resistance increase very quickly because it turns from superconducting state to normal state just like we use a little power to suppress the *I-V* curve from bias point A (superconducting state) to bias point B (a small section of the HEB becomes normal state) as shown in Fig. 6. So we can estimate the $C_{0n}$ from the change of resistance from A to B and the RF power absorbed by the bolometer. $V_A$=1.005 mV, $I_A$=98 $\mu$A, $V_B$=0.88 mV, $I_B$=76 $\mu$A, so the $\Delta R$ from A to B is 1.324 Ω. As the *I-V* curves are measured using two-probe method, we should correct the effect of contact resistance, when we calculate the absorbed DC power and RF power. From the *I-V* curves, we know the contact resistance $R_c$ is 8.33 Ω. So the absorbed DC power from bias point A to B is $P_{DC} = I_A(V_A - R_cI_A) - I_B(V_B - R_cI_B) = 0.277$ nW. And we can calculate the absorbed RF power ($P_{RF}$) of curve 2 using the isothermal method together with correcting the effect of contact resistance, the result is 0.8 nW. So the $C_{0n}$ at the edge section is $\Delta R/(P_{DC} + P_{RF})$=1.229 Ω/nW. And

**Table 1** Lowest receiver noise temperatures and conversion losses at different frequencies for different AR coating conditions.

| AR conditions \ f | 0.65 THz | 1.6 THz | 2.5 THz | 3.1 THz |
|---|---|---|---|---|
| No AR | 1028 K<br>33 h*f*/k$_B$<br>14.3 dB | 1165 K<br>15.2 h*f*/k$_B$<br>14.3 dB | 1396 K<br>11.6 h*f*/k$_B$<br>14.7 dB | 1734 K<br>11.7 h*f*/k$_B$<br>16.4 dB |
| 0.65 THz AR | 698 K<br>22.4 h*f*/k$_B$<br>12.9 dB | 1057 K<br>13.8 h*f*/k$_B$<br>13.5 dB | 1462 K<br>12.2 h*f*/k$_B$<br>15.2 dB | 1386 K<br>9.31 *f*/k$_B$<br>12.79B |
| 2.5 THz AR | 1278 K<br>41 h*f*/k$_B$<br>17.7 dB | 904 K<br>11.8 h*f*/k$_B$<br>13.0 dB | 1026 K<br>8.56 h*f*/k$_B$<br>12.0dB | 1401 K<br>9.42 h*f*/k$_B$<br>12.9 dB |

we can calculate the whole $C_0$ of the bridge at the optimized bias point from the *I-V* curves at point C and point D. $V_C$=1.25 mV, $I_C$=30 $\mu$A, $V_D$=1.25 mV, $I_D$=25 $\mu$A, so the $\Delta R$ from C to D is 8.3 Ω. The DC power absorbed from C to D is $P_{DC} = I_C(V_C - R_cI_C) - I_D(V_D - R_cI_D) = 3.69$ nW, the absorbed RF power from the curve 4 to curve 5 is $P_{RF}$ = 135 nW − 110 nW = 25 nW. So $C_0$ at the optimized bias point is 0.3945 Ω/nW. Since $C_0$ is the average value of $C_{0n}$ in each section, it will be

$$C_0 = \frac{1}{N}\sum_{n=1}^{N} C_{0n} \tag{4}$$

$C_{0n}$ at the edge section is 1.229 Ω/nW. The whole $C_0$ at the optimized bias point is 0.3945 Ω/nW, then the $C_{0n}$ at the non-edge sections is much smaller than the $C_{0n}$ at the edge sections, and do not influence the $\beta$ very much. Thus when we calculate the $\beta$ from Eq. (3), we can assume the $C_{0n}$ in the non-edge sections are at the same value, and from Eq. (4), we get $C_{0n}$ at non-edge section is 0.186 Ω/nW. Together with $N$=10, $I_0$=25 $\mu$A (optimized bias current) and $C_{0n}$ at the edge section 1.229 Ω/nW, we can get $\beta$ of 3.75 from Eq. (3).

In order to quantify the effect of the quantum noise to the receiver noise, we also measured $T_N$ and $L_{total}$ at different LO frequency and AR conditions with the same mixer chip. The results are summarized in Table 1. The lowest $T_N$ are 698 K at 0.65 THz, 904 K at 1.6 THz, 1026 K at 2.5 THz and 1386 K at 3.1 THz.

From the equation (see details in [17]):

$$\begin{aligned} T_{Rec}^{DSB} = {} & (L_{300} - 1)T_{300K} + (L_{300}L_{77} - 1)T_{77K} \\ & + \frac{hf}{2k}[L_{300}L_{77}L_4 \cdot \beta - 1] + \frac{L_{300}L_{77}L_4 \cdot \beta}{2G_{IBBM}} \\ & \times (T_{CL,MIX}^{out} + T_{IF,Amp}) \end{aligned} \tag{5}$$

where $L_{300}$, $L_{77}$, $L_4$ are the optic loss at 300 K, 77 K and 4.2 K, respectively, $G_{IBBM}$ is the conversion gain of an ideal

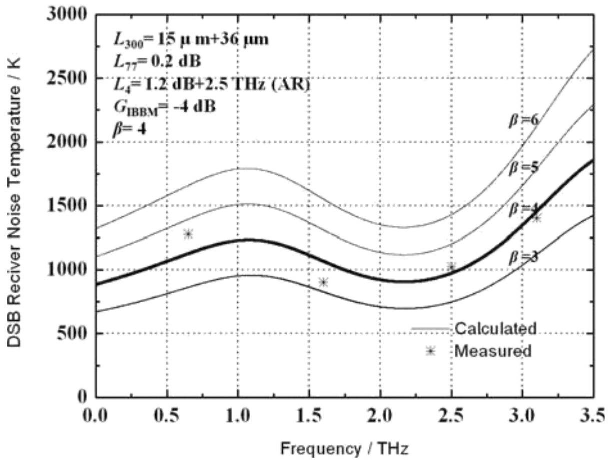


**Fig. 7** Frequency dependence of lowest noise temperatures for a Parylene C AR coating on the Si lens with thickness of 18.5 $\mu$m (2.5 THz). $\beta$=4 was obtained and agree well with the calculated value (lines).

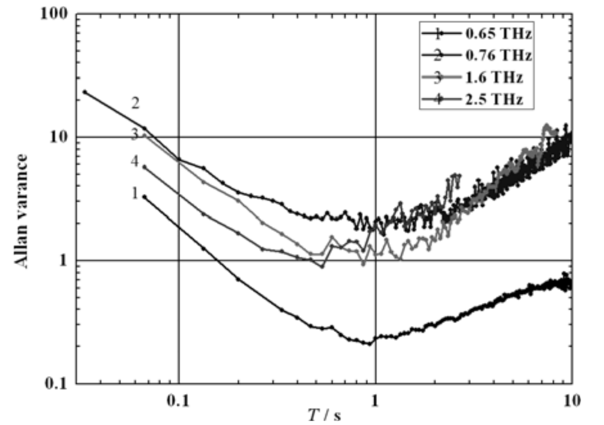


**Fig. 8** Allan variance $\sigma_{\mathrm{A}}^2(T)$ of the IF output power of the HEB as a function of the average period. Curve 2, 3 and 4 are with the FIRL as LO sources at 0.76, 1.6 and 2.5 THz. Curve 1 is for a Gunn oscillator with its multipliers at 0.65 THz as an LO source.

broadband mixer and can be calculated from the equation $L_{total}\,(\mathrm{dB}) = -G_{IBBM} + \beta + L_{optic}$ or $\beta/G_{IBBM} = L_{total}/L_{optic}$, $T_{CL,MIX}^{out}$ is the classical noise of HEB mixers, the typical magnitudes are 40–50 K, $T_{IF,Amp}$ is the noise temperature of IF amplifier, we got Fig. 7. The excess quantum noise factor $\beta$ of about 4 (= 6 dB) can be estimated, which is very close to the calculated value 3.75 as we just obtained. Also, $G_{IBBM}$=−4 dB can be calculated and is a reasonable value as assumed in [17].

The early report has shown that the calculated conversion gain and noise temperature of an HEB mixer in a small signal model does not agree with the experiments, unless the RF heating efficiency is adjusted [20]. Here, by introducing the quantum noise, we successfully fit the experiments, while giving a relative small $\beta \approx 4$. This $\beta$ meets the estimation from the distributed phonon-cooled bolometer model. The low $\beta$ value achieved in our experiments implies that in the reasonable near future HEB receiver can work up to 10 THz with a noise temperature of $10{\times}\mathrm{h}f/\mathrm{k_B}$ or better [17].

### 3.3 Stability and Temperature Resolution

As the stability of the receivers is one of important factors for the applications, we also measured the Allan variance $\sigma_{\mathrm{A}}^2(T)$ of the IF output power to determine the stability of the HEB operating at the optimal bias point, where the lowest noise temperature is obtained. The Allan variance is defined as $\sigma_{\mathrm{A}}^2(T) = \sigma_{\mathrm{D}}^2(T)/2$, where $\sigma_{\mathrm{D}}^2(T)$ is variance of the difference of contiguous measurements at averaging time $T$ [21]. We record the IF output power as a function of time. Then calculate the Allan variance $\sigma_{\mathrm{A}}^2(T)$ of our receiver system with different averaging time $T$. The result is plotted in Fig. 8. We use the FIRL as the LO sources at 0.76, 1.6 and 2.5 THz and the Allan time $T_A$ is about 0.433 s, 0.467 s and 0.533 s, respectively. In the same figure also include the Allan variance using a Gunn oscillator with its multipliers at 0.65 THz as the LO source and the $T_A$ is about 0.933 s. The increase of the Allan time is because the output power of the Gunn oscillator with its multipliers is more stable than the output power of the FIRL. These Allan time at 0.65, 0.76, 1.6 and 2.5 THz are almost same with published results [6] and should be improved for the astronomical applications, although there are no requiements for it at this moment [10]. To get the informations for the applications on THz imaging, we also estimate the temperature resolution [22] from the Allan variance data of Fig. 8. We obtained the temperature resolution of 1.1 K using the Gunn oscillator at 0.65 THz and the integration time of 0.933 s. Using the FIRL as LO sources we obtained the temperature resolutions of 4.37 K, 5.54 K and 6.18 K at 2.5 THz, 1.6 THz and 0.76 THz, with the integration times of 0.533 s, 0.467 s and 0.433 s, respectively. The deterioration of resolution using the FIRL as an LO is attribute to the slow drift noise and $1/f$ noise mainly from the instability of the LO sources. The variation of the temperature resolution at different frequency using the FIRL as an LO is due to the difference of the integration time.

## 4. Conclusions

The receiver performances of the quasi-optical superconducting NbN HEB mixers have been investigated from 0.65 THz to 3.1 THz. The lowest DSB noise temperature measured at 2.5 THz is 1026 K without correction. The excess quantum noise factor $\beta$ of about 4 has been obtained which agrees well with the calculated value. Stability of the system was measured, and Allan time $T_A$ longer than 0.4 s was obtained. From the Allan variance, we charaterize the temperature resolution of the HEB and have got the minimum temperature resolution of 1.1 K, using a Gunn oscillator with its multipliers at 0.65 THz and the integration time of 0.933 s. This mixer is a good one with a low noise temperature and can support the quantum noise theory quite well.

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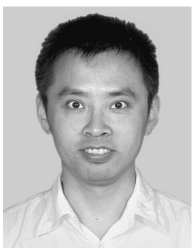

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