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

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1. Introduction

Heterodyne mixers based on hot electron bolometers (HEBs) combine excellent noise performance and lower local oscillator (LO) power requirement at terahertz (THz) waveband. Below 1.4 THz, Superconductor-Insulator-Superconductor (SIS) mixers exhibit noise temperatures quite close to the quantum limit $T_Q = \hbar f / k_B$ (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 K at 3.1 THz [10]. It can be expected that HEB mixers will be used widely at THz frequency band in the future. Here, we report the fabrication and properties of low noise receivers based on niobium nitride (NbN) HEB mixers at THz frequency band.

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+N₂ 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 μm square. Its critical temperature ($T_c$) of about 9 K and critical current density of about $1.5 \times 10^6$ A/cm² 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 thickness of about 50 nm is deposited and then we use photolithography and selective ion etching to keep the width of the bolometer bridge. The bridge is fabricated with the thickness of 4 nm, length of 0.4 μm and width of 3 μm. 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 $\lambda_{0,\text{max}} / 4$ and inner diameter smaller than $\lambda_{0,\text{min}} / 20$, where $\lambda_{0,\text{max}}$ and $\lambda_{0,\text{min}}$ are the maximum and minimum wavelength in the free space, respectively [12]. The picture of the HEB mixer is shown 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 separated 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 filters.
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 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 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 around 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 impedance 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 $T_Q=hf/k_B$ 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. Then we obtain the $L_{total}$ at the optimal bias point is 12.0 dBF 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).

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,

$$\sum_{n=1}^{N} R_{0n} = R_0 \equiv V_0/I_0$$  \hspace{1cm} (1)

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

$$C_{Qn}^{RF} = \left( \frac{\partial R}{\partial P_{RF}} \right)_n \Delta x \quad C_{Qn}^{DC} = \left( \frac{\partial R}{\partial P_{DC}} \right)_n \Delta x$$  \hspace{1cm} (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 $P_{Qn}=hfB\beta$. And $\beta$ can be calculated as

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

So we need to know $C_{Qn}^{RF}$ and $C_{Qn}^{DC}$ 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 $C_{Qn}^{RF} = C_{Qn}^{DC}$ in each section, (the whole $C_{Qn}^{RF}$ and $C_{Qn}^{DC}$ 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].

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.
the resistance increase very quickly because it turns from superconducting state to normal state just like we use a light bulb. The resistance increase very quickly because it turns from superconducting state to normal state just like we use a light bulb. The resistance increase very quickly because it turns from superconducting state to normal state just like we use a light bulb. The resistance increase very quickly because it turns from superconducting state to normal state just like we use a light bulb. The resistance increase very quickly because it turns from superconducting state to normal state just like we use a light bulb.

So 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 $\Omega$. The DC power absorbed from C to D is $P_{DC} = I_{C}(V_{C} - R_{C}) - I_{D}(V_{D} - R_{D}) = 3.69$ 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 $\Omega$/nW. Since $C_0$ is the average value of $C_0n$ in each section, it will be

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

(4)

$C_{0n}$ at the edge section is 1.229 $\Omega$/nW. The whole $C_0$ at the optimized bias point is 0.3945 $\Omega$/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 we can 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 $\Omega$/nW. Together with $N=10$, $I_0=25 \mu A$ (optimized bias current) and $C_{0n}$ at the edge section 1.229 $\Omega$/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]):

$$T_{Rec}^{DSB} = (L_{300} - 1)L_{300K} + (L_{300}L_{77} - 1)T_{77K}$$
$$+ \frac{hf}{2k}[L_{300}L_{77}L_4 \cdot \beta - 1] + \frac{L_{300}L_{77}L_4 \cdot \beta}{2G_{BBM}} \times (T_{out}^{CLMIX} + T_{IF,Amp})$$

(5)

where $L_{300}$, $L_{77}$, $L_4$ are the optic loss at 300 K, 77 K and 4.2 K, respectively, $G_{BBM}$ is the conversion gain of an ideal
The distributed phonon-cooled bolometer model. The low noise temperature of 10 THz with a noise temperature of 10^26 K in the reasonable near future HEB receiver can work up to 0.65 THz with a noise temperature of 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, $G_{1BBM} = -4$ 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 if in the reasonable near future HEB receiver can work up to 10 THz with a noise temperature of 10^26 K 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 $\sigma_A^2(T)$ 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 $\sigma_A^2(T) = \sigma_T^2(T)/2$, where $\sigma_T^2(T)$ 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 $\sigma_A^2(T)$ 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. 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 attributed 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 characterize 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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References


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