Appropriate microwave frequency selection for biasing superconducting hot electron bolometers as terahertz direct detectors

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Abstract

Terahertz (THz) direct detectors based on superconducting niobium nitride (NbN) hot electron bolometers (HEBs) and biased by a simple microwave (MW) source have been studied. The frequency and power of the MW are selected by measuring the MW responses of the current–voltage (I–V) curves and resistance–temperature (R–T) curves of the NbN HEBs. The non-uniform absorption theory is used to explain the current jumps in the I–V curves and the resistance jumps in the R–T curves. Compared to the thermal biasing, the MW biasing method can improve the sensitivity, make the readout system much easier and consumes less liquid helium, which is important for long lasting experiments. The noise equivalent power (NEP) of 1.6 pW Hz\(^{-1/2}\) and the response time of 86 ps are obtained for the detectors working at 4.2 K and 0.65 THz.

Keywords: terahertz, direct detector, microwave biasing, superconducting hot electron bolometer, noise equivalent power

(Some figures may appear in colour only in the online journal)

Introduction

Superconducting niobium nitride (NbN) hot electron bolometers (HEBs) have been used successfully in astronomical observations \cite{1–3} and as ultra-sensitive terahertz (THz) heterodyne detectors (mixers) with low noise temperature \((T_N, \text{about a few times the quantum limit})\) \cite{4}. Apart from heterodyne detectors, with excellent noise performance and large intermediate frequency (IF) gain bandwidth (GBW) \cite{5}, NbN HEBs would be promising as direct detectors for the THz imaging array, where heterodyne detectors are very difficult to use due to needs of the local oscillators (LO) and IF amplifiers.

NbN HEBs as direct detectors using thermal biasing have been investigated by several groups \cite{6, 7}. In this method, a heating resistor fixed on the holder is used to heat the HEB up to its critical temperature \((T_c)\). The most sensitive performance would be achieved around the \(T_c\) because there is a strongest nonlinearity point here in the resistance–temperature \((R–T)\) curve. But this method consumes much liquid helium due to the heating resistor needing to heat the whole holder, which has a good thermal contact with the cold plate of the dewar. It would be a crucial problem for long lasting usage in the THz astronomical observation or security check area. According to the hot spot model’s viewpoint, electromagnetic waves (EMWs) can be absorbed by a superconducting bridge and a hot spot (temperature higher than \(T_c\)) will develop in the middle region (bridge). Since EMWs only heat the bridge
with a little power (<1 μW), this method consumes far less liquid helium compared to the thermal biasing method. EMW radiation may be used to bias the HEB instead of the thermal biasing for the sake of long lasting usage. But for now, THz sources are still expensive for many applications. Moreover, when the HEB is biased by THz radiation, the beam splitter coupling the radiation into the dewar window would make the system more complicated. Compared to THz sources, microwave (MW) sources are more mature, smaller and easier to use [7, 8]. Also MW can be guided by the coaxial line to the HEBs. Furthermore, MWs can be used for an easy read-out, which has been used in the other direct detector system [9]. All of the above points would make the direct detector using MW biasing simpler than the system using THz biasing. But how to select appropriate MW frequency is still a crucial problem in the MW biasing method at the present stage. Stability and sensitivity of direct detectors with MW biasing should be considered in choosing the appropriate MW frequency. Here, we demonstrated one of the MW biasing methods and proposed a method to choose the appropriate MW frequency in constructing the sensitive direct detectors.

**Experimental setup**

The NbN HEB chip we used consists of a 4 μm wide, 0.4 μm long and 3.5 nm thick NbN bridge on a highly resistive silicon (Si) substrate which has a good transmittance in the THz band. A logarithmic spiral planar antenna with frequency independent impedance and no polarization direction is used to couple THz signals to the bridge. The chip is glued to the back side of a Si hyper-hemispherical lens with a diameter of 10 mm. The Si lens is coated with a 0.65 THz anti-reflection (AR) coating for reducing the optical loss of the incident THz signals. An oxygen-free copper holder used to hold the Si lens is installed on the cold plate of the liquid helium dewar. The optical window is made of mylar film which has a good transmittance for THz radiation with a thickness of 36 μm. Two black polyethylene films and one G-110 Zitex polytetrafluoroethylene film are used in the dewar input hole at a 77 K thermal shielding frame as infrared filters. In order to calculate the input radiation power using Planck's blackbody radiation law, a piece of Virginia Diodes Inc. (VDI) mesh-filter in the holder located between the dewar window and the HEB holder is used to define the input bandwidth of this system. The mesh-filter is centered at 0.623 THz and yields a bandwidth of 75 GHz measured by THz time-domain spectrometer (TDS).

In this paper, the experimental setup as shown in figure 1 is similar to the MW stabilization scheme setup constructed in our lab [10]. A 20 dB attenuator is located on the cold plate of the dewar for avoiding the 300 K ambient background noise. The circulator is used to inject MW to the NbN HEB without being picked up by the low noise amplifier (LNA) directly. The reflected weak MW signal from the NbN HEB is amplified by the LNA and demodulated by a MW square-law detector (power detector), finally fed to a dynamic signal...
Results and discussions

In order to evaluate the performance of the NbN HEB, we measured its $T_N$ at the LO frequency of 0.65 THz and bath temperature of 4.2 K. The improved Y-factor method [11] is used to measure the $T_N$ for avoidance of the direct detection effect. The IF output power, $P_{\text{hot}}$ and $P_{\text{cold}}$, corresponding to the hot and cold loads, are measured at the same bias voltage to get $Y = P_{\text{hot}}/P_{\text{cold}}$. The uncorrected $T_N$ can be calculated by the following expression [12]:

$$T_N = \frac{T_{\text{hot}}-YT_{\text{cold}}}{Y-1}.$$  \hspace{1cm} (1)

The lowest $T_N$ of 500 K (uncorrected, about 16 times the quantum limit) has been obtained at the optimum bias point ($V_{\text{bias}} = 1.25$ mV, $I_{\text{bias}} = 23$ $\mu$A) that was described in detail in [13]. The low $T_N$ means the NbN HEB chip’s quality is good and the IF circuit matches the chip well. We expected that a low noise equivalent power (NEP) of the direct detector using this chip with MW biasing would be achieved. In order to obtain the response time of the NbN HEB, we measured the IF GBW of this chip at the optimum bias point. Two VDI THz sources, with one fixed at 0.65 THz, and the other tuned around 0.65 THz are used to determine the IF GBW. The IF GBW of 1.85 GHz is obtained. According to the following expression, the response time $\tau$ of the NbN HEB is about 86 ps calculated by the following expression [14]:

$$f_{IF,3dB} = \frac{1}{2\pi\tau},$$  \hspace{1cm} (2)

where $f_{IF,3dB}$ is the IF GBW.

How to choose an appropriate MW frequency is a key problem for the MW biasing method. A study of the $I-V$ curves was performed when a NbN HEB was pumped by different MW frequencies and power. Two distinct frequency regimes divided by the IF GBW were found by comparing the MW responses of the $I-V$ curves in the MW range [15]. Although the exact mechanism is still not clear, the investigation of $I-V$ curves pumped by different frequencies would give us some clues in choosing an appropriate MW frequency for biasing the HEB. In order to guarantee the MW frequency we choose is appropriate, we measured the MW responses of the $I-V$ curves with the MW frequencies around the IF GBW as shown in figures 2 and 3. It is noticeable that in figure 2(c), a steep current jump of the bottom $I-V$ curve is observed when the critical current reaches 75 $\mu$A. This phenomenon also can be seen in figure 2(d). There is a large blank region in both figures where $I-V$ curves cannot reach because slight MW power changes will cause current jumps and miss this region. As for the heterodyne detection, the optimum bias point of NbN HEBs always appears in this region. This means when the MW frequency is higher than IF GBW, we cannot stabilize the working state of the NbN HEB in the sensitive region.

$I-V$ curves with a 1.5 GHz injection as shown in figure 2(b) are most similar to the $I-V$ curves with thermal biasing as shown in figure 2(a). With a 1.5 GHz MW injection, we can scan the whole $I-V$ region to find a stable bias point and get the lowest NEP. In order to confirm our judgment, we also measured the $R-T$ curves of the HEB with 1.5 GHz and 3 GHz MW injections as shown in figure 3. When the injection MW frequency is set to 3 GHz, both the two $R-T$ curves with MW injections have steep resistance jumps which correspond to the current jump of the $I-V$ curves obtained in figure 2(d). Although a sharp transition in the $R-T$ curve means high temperature coefficient resistance (TCR) which can be used to describe the sensitivity of bolometers, it is difficult to stabilize the biasing point at the resistance jump region in the practical application.

The non-uniform absorption theory was proposed to explain the current jumps in the $I-V$ curves and resistance jumps in the $R-T$ curves when the EMW frequency is lower than the superconducting energy gap frequency [16]. Although the authors only discussed the $I-V$ curves and the $R-T$ curves with THz radiation, this theory would be fitted to explain the $R-T$ curves with MW injection. It is well known that when the superconductor’s temperature rises, the superconducting energy gap frequency will drop towards zero. Referring to the middle curve in figure 3(b), when the temperature is below about 6.6 K, the MW frequency of 3 GHz is lower than the superconducting energy gap frequency, so the NbN HEB absorption efficiency is very low and the NbN HEB is kept in the superconducting state. As the HEB temperature rises, the superconducting energy gap frequency will decrease to 3 GHz and then the NbN HEB absorption will increase substantially, which causes the resistance jump. It also can be seen that resistance jumps are more likely to appear at the higher temperature with a 3 GHz MW injection compared to the $R-T$ curves with 1.5 GHz MW injections in figure 3(a). We attribute this difference to the unknown heating mechanism related to the IF GBW that merits further in-depth studies in the future.

When the injected MW frequency is 1.5 GHz, the two $R-T$ curves without resistance jumps have sharper transitions compared to the $R-T$ curve without MW injection. A higher responsivity will be achieved at $T_c$ of the $R-T$ curve with appropriate MW power injection compared to the thermal biasing method. Based on the discussions above, we chose 1.5 GHz MW to bias the HEB as a direct detector and expect a better performance compared to the thermal biasing method.

In order to investigate the working scheme of this system, we use a VDI THz source with a frequency of 0.65 THz and low emission power as a weak signal, which can be detected, but do not change the current at the optimum bias point, in front of the dewar window. Figure 4 is the output signal’s spectrum from the LNA output port. The center frequency is about 1.5 GHz (a slight deviation from 1.5 GHz is caused by the MW source), which is consistent with the injection MW frequency. Two sidebands located in both sides and the offset frequency is the same as modulation frequency $F_m$. When we decrease the modulation frequency of the chopper, two sidebands move...
toward the center peak and the offset frequency keeps the same as $F_{m}$. From this phenomenon we can conclude that the side-bands are caused by the incident signal which is modulated by the chopper. The modulated incident THz signal changes the HEB impedance so the reflection coefficient of the MW network is also changed and the MW signal reflected by the HEB is indirectly modulated by the chopper.

NEP is one of the key parameters of the direct detectors. In order to measure the NEP of the NbN HEB direct detector using MW biasing, a blackbody radiation source with temperature set to $T_B$ was used to provide the incident THz signal. The NEP measurement was performed at different MW frequencies, with the optimum bias point chosen as shown in Figure 2. The current jumps observed at MW frequencies higher than the IF GBW indicate the onset of the THz coupling process.

Figure 3. $R$–$T$ curves with (circles) and without (dashed lines) MW injections.

Figure 4. Spectra of the output power measured at the output of the LNA with $F_m$ at 1.384 kHz (a) and 1.2 kHz (b). The bias setting was $V_{bias} = 1$ mV, $I_{bias} = 31$ μA.
chopper between them. With the input bandwidth defined by the VDI mesh-filter, the input radiation power of 0.8 nW is calculated by using Planck’s blackbody radiation law. The chopping frequency is set to 1.37 kHz. In order to obtain the lowest NEP, we scan all regions under the unpumped $I-V$ curve and get the optimum bias point which is marked in figure 2(b). At this bias point, the digital spectrum at 1.37 kHz rises to about 508 times the baseline of the noise voltage spectrum with a resolution bandwidth of 1 Hz. We figure out the NEP is 508 times lower than 0.8 nW, therefore, the NEP at the optimum bias point is 1.6 pW Hz$^{-1/2}$ which is better than the thermal biasing NbN HEB direct detector’s performance [6].

Conclusions

In conclusion, we have investigated the MW responses of the $I-V$ curves and the $R-T$ curves. With the non-uniform absorption theory, we can explain the current jumps in the $I-V$ curves and the resistance jumps in the $R-T$ curves well. An appropriate frequency of MW was selected to bias the NbN HEB. The injected MW serves two purposes for biasing the HEB to the optimum point and reading out the small impedance change of the HEB caused by the input THz signals variation. We monitored the output MW power from the LNA and obtained the work scheme of this method. The NEP of 1.6 pW Hz$^{-1/2}$ is obtained and can be expected to be improved by optimizing the readout circuit in the near future.

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