Direct detection behavior of a superconducting hot electron bolometer measured by Fourier transform spectrometer

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ABSTRACT

In this paper, the direct detection behaviors of a superconducting hot electron bolometer integrated with a log spiral antenna are investigated by using Fourier Transform Spectrometer (FTS). We find the response of the bolometer to a modulated signal can be detected by a lock-in amplifier not only from the DC bias current, but also from the output noise power at the IF port of the HEB. We attribute the response in output noise power to Johnson noise and thermal fluctuation noise. Both the current response and the output noise power response measured at different bias voltages can be explained by one dimensional distributed hot spot model. In addition, the frequency response of the hot electron bolometer measured from the response in DC bias current is in good agreement with that in IF output noise power.

Keywords: Superconducting hot electron bolometer, direct response, hot spot model, THz.

1. INTRODUCTION

Superconducting hot electron bolometer mixers are currently the most sensitive devices for coherent detection in the THz frequency range, and have been successfully used to detect spectral lines in APEX ground telescope [1] and HIFI on Herschel space observatory [2]. One of the key factors that may affect the sensitivity performance of superconducting HEB mixers is the coupling of the free-space RF radiation to bolometer. Usually frequency response of superconducting HEB mixers is characterized by Fourier Transform Spectrometer (FTS) with a broadband radiation source (i.e. Hg arc lamp or Globar). In this paper, we measured not only the DC bias current response but also the IF output noise power response of the superconducting HEB by using Fourier Transform Spectrometer. The measured results were compared to the calculations based on one dimensional distributed hot spot model. Furthermore, the frequency response of the superconducting HEB integrated with the log spiral antenna was measured and the influence of the operating point of the device on the frequency response was also examined.

2. QUASI-OPTICAL HEB DEVICE AND MEASUREMENT SETUP

The investigated quasi-optical NbN superconducting HEB device was fabricated at LERMA, France. The fabrication process of the superconducting HEB device is based on several electron beam lithography and lift-off steps [3]. As shown in Fig. 1, the HEB device itself is indeed 3.5 nm thick superconducting NbN film (called NbN microbridge)\textsuperscript{*}

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connected to a self-complementary log-spiral antenna, with an outer diameter of 400 μm and an inner diameter of 13 μm. This design is expected to cover the frequency range from 100 to 1400 GHz [4]. The NbN microbridge is chosen to be 0.2 μm long and 2.0 μm wide to get approximately 70-80 Ω, in good match with the log spiral antenna.

Fig. 1 Photograph of the measured NbN HEB device. The NbN microbridge is defined by 0.2 μm (L)×2.0 μm (W)×3.5 nm (T), and integrated with a log-spiral antenna.

The frequency response of the log spiral antenna coupled HEB is measured by using a Fourier Transform Spectrometer (see Fig. 2), which is essentially a Michelson interferometer [5]. The broadband radiation from a Mercury arc lamp is modulated by a chopper at about 10 Hz and the electrical response of the HEB is recorded by a lock-in amplifier that was synchronized with the chopper. The FTS is operated in a step-and-integrate mode. A Nanomotion motor [6] is used to drive the movable mirror with a maximum travel length of 60 mm and a step size less than 15 μm, which gives a frequency resolution of 2.5 GHz and a frequency bandwidth up to 5 THz.

Fig. 2 Photograph of the Fourier Transform Spectrometer

3. MEASURED RESULTS AND ANALYSIS

In order to achieve a high sensitivity, the HEB was intentionally heated to a temperature close to its superconducting
critical temperature $T_c$. Fig. 3 shows the measured current-voltage characteristics of the HEB at different bath temperatures. It should be pointed out that the temperature of the superconducting HEB device is 0.5~1 K higher than that of mixer block monitored by the temperature sensor. Fig. 3 also shows the current-voltage characteristics calculated by one dimensional distributed hot spot model [7], based on a heat balance equation for electron temperature along the superconducting microbridge. In the model, the measured temperature dependent resistance of the HEB device instead of a Fermi form assumption was adopted to determine the resistance of the device and the effect of bias current on the critical temperature of the HEB was also included [8], [9]. Our measurements below are performed at the temperature of 6.7 K.

![Fig. 3 I-V curves of the HEB at different temperatures](image1)

We first measured the response in DC bias current of the HEB with the experimental setup shown in Fig. 2. A 500 GHz solid state source (Gunn oscillator and frequency multiplier) instead of the Mercury arc lamp was used as signal in this measurement. The inset of Fig. 4 shows the measured current response of the HEB at one bias voltage. The peak at 500 GHz represents the signal detected by the HEB. Fig. 4 shows the measured current response of the HEB at different bias voltages. The maximum current response occurs at low bias voltage, where the best receiver noise temperature of the

![Fig. 4 Measured and calculated current response of the HEB at different bias voltages](image2)
HEB mixer is usually obtained. During the experiment, the output power of the signal source was kept constant for all bias voltages to get the relative current response. Note that the intrinsic coupling between the bolometer impedance and the impedance of the log spiral antenna (for this case ~75 $\Omega$ at 500 GHz) should be calibrated for the estimation of the current response. For comparison, based on one dimensional distributed hot spot model, the calculated current responsivity of the HEB is also shown in Fig. 4. The current responsivity of the HEB can be written as $S_R=(V/R_0)(\Delta R/\Delta P)$, where $R_0$ is DC resistance of the HEB at the bias voltage of $V$, $\Delta P$ and $\Delta R$ are the differences in signal power (Here 1 nW was assumed in the calculations) and in resulted resistance. The theoretical results are found to be in good agreement with the measurements over the whole bias voltage range. Results show that the HEB can be operated with a relative high current responsivity (larger than 100 A/W) in a wide voltage range (up to 1 mV).

We find the signal modulated by the chopper can also be detected by the lock-in amplifier from the output noise power at the IF frequency, i.e. 1.5 GHz. During the measurement, the output noise power of the HEB is amplified by a cooled low noise HEMT amplifier (~30 dB) and a room temperature amplifier (~35 dB). We attribute this response in output noise power to the modulation of Johnson noise and thermal fluctuation noise. They are the dominant noise sources in HEB mixers and can be written as [7]

$$T_{\text{out}}^\text{total} = \frac{4R_0R_LT_e + 4T_e^2I_0^2(\frac{\partial R}{\partial T})^2R_L/G}{(R_0+R_L)^2(1+C_{dc}I_0^2R_0-R_L/R_0+R_L)^2}$$

where $R_L$ is the load resistance, $T_e$ the temperature of the electrons in the microbridge, $C_{dc}$ the heat capacity due to the absorbed DC power, $G$ the thermal conductance given by $c_vV/\tau_\theta$. For a typical thin NbN film, the electron specific heat $c_v$ is about 1600 Ws/m$^3$K and the electron relaxation time $\tau_\theta$ is estimated to be 30 ps. Fig. 5 shows the measured and calculated response in output noise power of the HEB at different bias voltages. It can be seen that they have similar shape over the whole bias range.

![Fig. 5 Measured and calculated output noise power response of the HEB at different bias voltages](image)

Using the response in DC bias current and the response in output noise power, we obtained the frequency response of the hot electron bolometer (see Fig. 6). It is clear that two measurements give nearly identical results and the response of the HEB is in the frequency range from 200 to 1000 GHz. For frequencies higher than 1000 GHz, the response of the HEB becomes quite weak, in spite of the fact that the log spiral antenna should in principle operate in that frequency region in terms of the results (coupling between the antenna and the HEB microbridge) simulated by Microwave studio CST [10].
The possible reason is the absorption of the atmospheric water vapor since the entire FTS measurement system sits in air. Furthermore, the notches around 557 GHz and 752 GHz are also produced by saturated water absorption lines. These two notches are relatively obvious although the frequency resolution of the measurements is low, indicating that the absorption due to the water vapor is quite strong. In the measurement, the frequency resolution is chosen to be 40 GHz to achieve a high signal-to-noise ratio, which is about 50 and 45 in the HEB’s frequency responses obtained from the response in DC bias current and the response in output noise power respectively.

![Fig. 6 Frequency response of the HEB obtained from the response in current and in output power](image)

We also measured the frequency response of the HEB at different operating points of the HEB. The bias voltages and the bath temperatures were changed within the range where the HEB device is still sensitive and stable. Fig. 7 illustrates the measured frequency responses (based on the response in output noise power) at three different operating points. The inset of Fig. 7 is the measured interferogram of the HEB. Measured results show that only the magnitude of the frequency response is affected by the operating points and after normalization the general sharp of the frequency response does not depend on the operating point. It implies that the frequency responses of the HEB are determined by the intrinsic characteristics of the log spiral antenna and not by its operating points.

![Fig. 6 Measured frequency response of the HEB at different operating points](image)
4. CONCLUSION

We have investigated the direct detection behaviors of a superconducting hot electron bolometer with Fourier Transform Spectrometer. The measurements of the response in DC bias current and the response in output noise power of the HEB have been performed at different bias voltages. The measured responses in DC bias current and in output noise power are found to be in agreement with theoretical calculation based on hot spot modeling. In addition, the measured frequency response of the HEB integrated with a log spiral antenna is in the frequency range from 200 to 1000 GHz and is found to be independent of the HEB’s operating point.

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REFERENCE