Temperature Dependence of HEB Mixer Performance

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***Abstract*— The performance of the NbTiN HEB mixer has been measured at various bath temperatures. The mixer performance is almost constant below 7 K, but it is degraded rapidly above that temperature. The result is compared with the classical operation picture of the HEB mixer. From the temperature dependence of the performance, the power index, *n*, of the heat conductance is estimated to be 4-5 for our NbTiN mixer, confirming that our device operates by the phonon-cooling mechanism. The temperature-dependence experiment provides us with important information on the operation mechanism of HEB mixer.**

I. Introduction

Superconducting hot-electron bolometer (HEB) mixers are recognized as the most promising device for low-noise heterodyne detection in the THz region [1]. In particular, the quasi-optical NbN HEB mixer shows a good performance up to several THz. Receivers using the HEB mixers are adopted for radio astronomy and atmospheric chemistry, for instance, in Herschel Space Observatory, SOFIA, TELIS, and so on.

So far evaluation and optimization of the HEB mixer receivers have been performed mostly at the fixed temperatures (4 K or 2 K) by using liquid He. In a practical operation of the HEB mixer receivers on the ground-based telescopes, mechanical cryocoolers will be used. In this case, the laboratory conditions might not be reproduced, so that the bath temperature of the mixer is possibly changed. It is therefore important to know how much the mixer performance is degraded when the bath temperature is changed. Moreover, the temperature dependence of the mixer performance would provide us with novel information on operation mechanisms of the HEB mixers.

However, an only few studies have been reported for the temperature dependence of the HEB mixer performance, Skalare *et al.* [2] fabricated the diffusion cooled HEB mixer using Nb. This device showed the receiver noise temperature of 650 K (DSB) at the bath temperature of 2.2 K, whereas its performance was about 3000 K (DSB) at 4.3 K. For the NbN HEB mixer, Cherednichenko *et al.* [3] measured the receiver noise temperature at various bath temperatures from the motivation to reduce the necessary LO power. In the present paper, we report a systematic study on the temperature dependence of the NbTiN HEB mixer performance.

II. Measurements

A. Current Status of the Mixer Development

Our group is developing an HEB mixer receiver aiming at the THz observations of fundamental atoms and molecules in star-forming clouds from the ground-based telescopes. We are fabricating diffusion-cooled type and phonon-cooled type HEB mixers using Nb and NbTiN, respectively. We adopt our original procedure for fabrication [4, 5]. The HEB mixer element is mounted on a waveguide mixer block for the signal and local oscillator (LO) coupling, and is cooled down to 4 K by a compact two-stage Gifford-MacMahon cryogenic-cooler equipped with a helium-pot for temperature stabilization (Sumitomo RDK-101E). Its cooling capability is 0.1 W for the 4 K stage. Receiver performance is tested at 810 GHz (using a Gunn oscillator as the LO source), and the best receiver noise temperature of 500 K has been achieved for the NbTiN mixer [4].

B. Temperature-dependence Experiment

The NbTiN HEB mixer element used for the temperature-dependence experiment has a microbridge size of 0.48 μm in length, 1.49 μm in width, and 12 nm in thickness. This is slightly larger than the mixer element which gives the best performance [4]. By using an electric heater attached on the

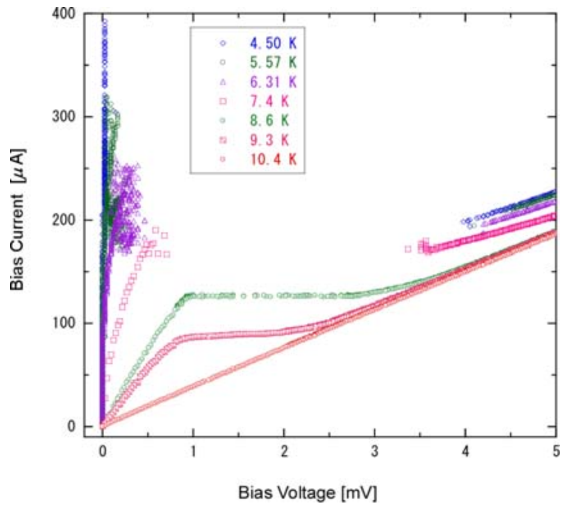

Fig. 1 I-V curves at various bath temperatures

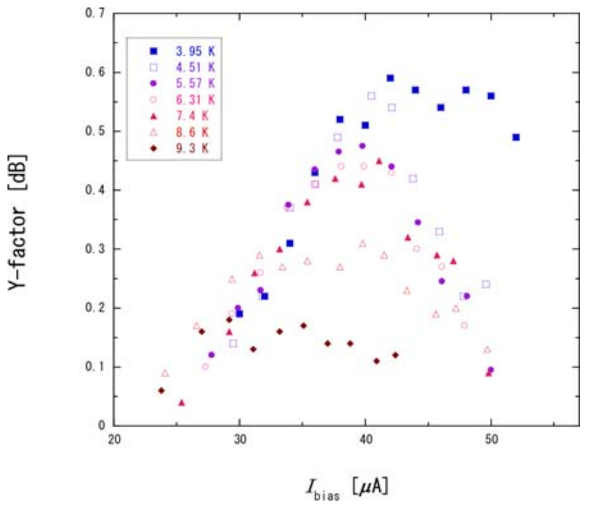

Fig. 2 Relation between Y-factor and I_{bias} at various T_{bath}. V_{bias} is fixed to 0.4-0.5 mV.

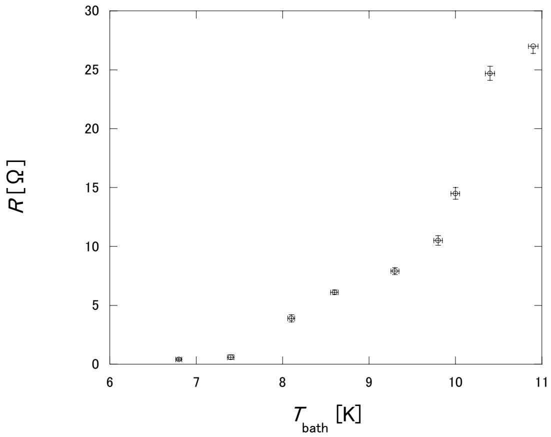

Fig. 3 R-T curve of the HEB device

cold stage, we can change the bath temperature easily.

Figure 1 shows the I-V curve of the mixer element measured at various bath temperatures. It is clearly seen that superconductivity disappears above 10.4 K. Therefore we have measured the Y-factor at various temperatures from 4 K to 9 K. In the measurements of the Y-factor, the bias voltage is kept constant (0.4-0.5 mV), and the bias current is adjusted by the LO input power; weaker LO input power gives higher bias current.

In Fig. 2, the Y-factor is plotted against the bias current at various temperatures. At 4.51 K, the Y-factor becomes the highest at the bias current of about 40 μA. For most cases, the best Y-factor is obtained at this bias current; namely the optimum bias point is independent on the bath temperature. This means that the effective operating resistance of the HEB mixer element is around 10-12 Ω at the optimum bias point, which just corresponds to the transition-edge in the R-T curve (Fig. 3). This result is consistent with the classical picture of the HEB mixer operation.

III. Discussions

Extensive efforts have been made to describe the operation principle of the HEB mixers [e.g. 6]. The receiver noise temperature (T_{RX}) is written as

$$T_{RX} = T_{MIX} + L_{MIX} T_{IF} \ , \tag{1}$$

where T_{MIX}, T_{IF}, and L_{MIX} represent the mixer noise temperature, the noise temperature of the IF amplifier, and the conversion loss of the mixer, respectively. In our case, the second term is found to be dominant. The conversion loss, L_{MIX}, can be written as

$$L_{MIX} = \frac{(Z_L + Z_B)^2}{2 S_0{}^2 P_{LO} Z_L} \propto \frac{1}{P_{LO}} \ , \tag{2}$$

where P_{LO}, S_0, Z_L, and Z_B, stand for the input local oscillator power, the voltage sensitivity, the load impedance, and the HEB device impedance, respectively. Since T_{MIX} also shows a similar dependence [6] and T_{IF} is almost constant below 10 K, T_{RX} is inversely proportional to P_{LO}. In addition, the heat balance between the input power and the thermal conductance makes the following equation;

$$P_{LO} + RI^2 = G_0 (T_C{}^n - T_{bath}{}^n) \ , \tag{3}$$

where G_0, T_C, and T_{bath} represent the thermal conductance, the critical temperature of the HEB device, and the bath temperature, respectively. For simplicity, we assume that the phonon temperature is equal to the bath temperature. In our case, the second term of the left hand side (DC heating), can be negligible in comparison with the first term, and hence, we obtain the following approximate relation,

$$T_{RX} \propto \frac{1}{T_C{}^n - T_{bath}{}^n} \ . \tag{4}$$

In the following part, we will test this classical picture by using the measurement result.

Figure 4 shows the receiver noise temperature (T_{RX}) as a function of P_{LO}, where P_{LO} is estimated from the isothermal method. T_{RX} is clearly inversely proportional to P_{LO}, confirming the above prediction. Next, the best receiver noise temperature is plotted as a function of the bath temperature in Fig. 5. When the bath temperature is raised, the performance is kept almost constant below 7 K, but is degraded rapidly above that temperature. This means that our NbTiN HEB mixer shows little change in performance against the bath temperature change around 4 K. This is in remarkable contrast with the Nb HEB case, which shows a strong dependence on bath temperature around 4 K [2]. This behavior of the NbTiN HEB mixer gives an important merit in practical operations on the telescopes.

From the relation between T_{RX} and T_{bath}, the index n of equation (4) is estimated to be 4-5, as shown in Fig. 5. This index is closer to the phonon-cooled case (NbN) (3.6) than to the diffusion-cooled case (Nb) (2.0). Our NbTiN device shows a quite similar behavior to the NbN device, confirming that our mixer is mainly operating by the phonon-cooling mechanism. The phonon-cooled NbTiN device has high T_C (about 10 K) and fairly large index n (4~5). On the other hand, T_C is relatively low (about 6 K) and n is small (2.0) in

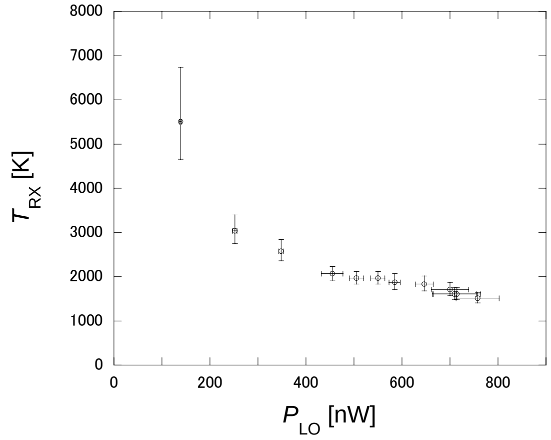

Fig. 4 Receiver noise temperature plotted against LO input power

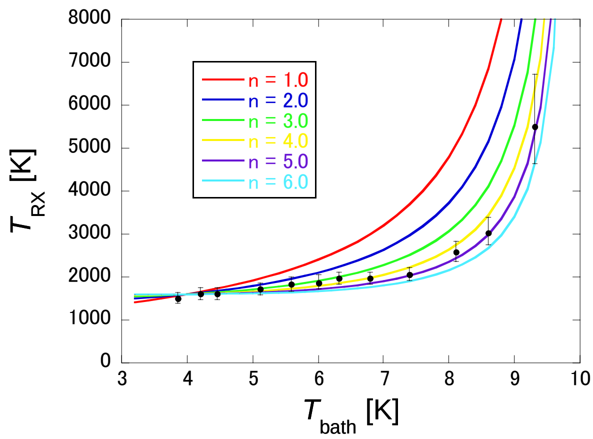

Fig. 5 Receiver noise temperature at various bath temperatures. Solid lines are fitted curves by equation (4), assuming that T_C = 10 K.

the case of the diffusion-cooled Nb device. This makes the strong temperature dependence around 4 K in the Nb device.

As described in this paper, we can estimate the index *n* quantitatively from the temperature-dependence measurement, which is an important parameter on the cooling mechanism of the HEB mixer. Needless to say, a similar experiment can be done by using the devices with different film thickness or different length of a superconducting microbridge. However, such experiments need fabrications of several devices of different sizes, and the performance may easily be affected by the characteristics of individual devices, the electrical contact, or the alignment conditions in an assembling process. In contrast, the temperature-dependence measurement can be carried out with a single device under the same environment. This method is therefore advantageous to investigate the operation mechanism of HEB mixer.

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