

## Influence of the direct response on the heterodyne sensitivity of hot electron bolometer mixers

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We present a detailed experimental study of the direct detection effect in a small volume ( $0.15 \mu\text{m} \times 1 \mu\text{m} \times 3.5 \text{ nm}$ ) quasioptical NbN phonon cooled hot electron bolometer mixer at 673 GHz. We find that the small signal noise temperature, relevant for an astronomical observation, is 20% lower than the noise temperature obtained using 300 and 77 K calibration loads. In a separate set of experiments we show that the direct detection effect is caused by a combination of bias current reduction when switching from the 77 to the 300 K load in combination with the bias current dependence of the receiver gain. The bias current dependence of the receiver gain is shown to be mainly caused by the current dependence of the mixer gain. © 2006 American Institute of Physics. [DOI: 10.1063/1.2234802]

### I. INTRODUCTION

Quasioptical NbN phonon cooled hot electron bolometer (HEB) mixers are currently the most sensitive heterodyne detectors at frequencies above 1.2 THz,<sup>1,2</sup> and they are increasingly being used as mixing elements in heterodyne terahertz receivers.<sup>3-5</sup> For a successful operation of such a receiver it is of vital importance that the local oscillator (LO) power requirement of the HEB mixer is compatible with the low output power of present day terahertz LO sources.<sup>6</sup> This is achieved by using small volume HEB mixers, consisting of  $\sim 4$ -nm-thick bridge of NbN with a length of  $\sim 150$  nm and a width of  $\sim 1 \mu\text{m}$ . Such a device needs about 50–100 nW of LO power to reach its optimal operating region.<sup>7</sup> The RF radiation is in most cases coupled quasioptically to the NbN bridge by means of a twin slot or spiral antenna, with typically a bandwidth of about 1 THz at a center frequency of about 1.5–2 THz. For a correct operation of the receiver one has to calibrate the mixer sensitivity, expressed in the double sideband receiver noise temperature  $T_N$ . This is normally done by calculating  $T_N$  from a measurement of the  $Y$  factor,<sup>8</sup>  $Y = P_{\text{hot}}/P_{\text{cold}}$ . Here  $P_{\text{hot}}$  is the receiver output power with a 300 K blackbody hot load as calibrated signal source, and  $P_{\text{cold}}$  the receiver output power with a 77 K blackbody cold load as calibrated signal source. Due to the thermal nature of the HEB mixer it is only the RF power within a few gigahertz around the LO power frequency that is mixed properly into an intermediate frequency (IF) signal.

The vast majority of the radiated power from the calibration load is simply absorbed in the HEB, raising the time averaged electron temperature in the device the same way as the LO power. For a typical 1.6 THz twin slot antenna the total power from a 300 K load within the antenna bandwidth of the mixer is of the order of 2–3 nW, which is a few percent of the total amount of LO power that is needed to bring the mixer to its optimal operating point. Hence switching from a 300 K to a 77 K load is expected to slightly change the pumping level of the mixer, noticeable by a reduction in bias current. This is the direct response, or direct detection effect, of a HEB mixer.<sup>9-13</sup> As a consequence, the bias point of the mixer is set not only by the voltage and the LO power, but by the voltage, LO power, and the load temperature. The direct detection effect will always be present together with the normal heterodyne response, but for a small volume, quasioptical HEB mixer the effect is the most prominent given the combination of low LO power need and large antenna bandwidth of these devices. To illustrate this we show, in Fig. 1, the  $IV$  curves at hot and cold load of a small volume quasioptical HEB mixer with an optimal amount of LO power supplied to the mixer.<sup>14</sup> The  $IV$  curve at hot load is clearly below the one at cold load. From the observed  $IV$  curves we can define a direct detection current  $I_{\text{DD}} = I_{\text{hot}} - I_{\text{cold}}$ , with  $I_{\text{hot/cold}}$  the HEB bias current at hot/cold load. The consequence is that we evaluate  $P_{\text{hot}}$  at a lower bias current than  $P_{\text{cold}}$  when we measure the  $Y$  factor.

To understand the consequence of the direct detection effect on the measurement of the  $Y$  factor we first have to imagine what would happen if we observe, with the receiver

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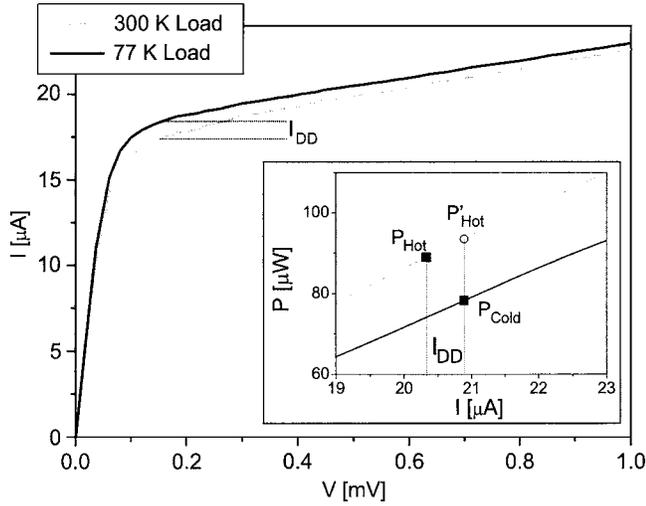


FIG. 1. IV curves for a small volume HEB mixer at the optimal pumping level, shown with a hot 300 K blackbody as signal source and with a 77 K cold blackbody as signal. The inset shows the receiver output power as a function of bias current at  $V=0.57$  mV. The black squares represent the output power at hot and cold load at one bias point, i.e., at one bias voltage and at a constant LO power. The points are shifted due to the presence of  $I_{DD}$ .  $P'_{hot}$  represents the hot load output power at the same bias current as at cold load.

discussed here, an astronomical source which represents itself as a small input power change on top of a background with an identical power input as our 77 K load. A small input power change is in this context defined as a power change that results in a negligible value of  $I_{DD}$ . To obtain the receiver noise temperature in this case we need to evaluate the small signal  $Y$  factor. The latter is defined as  $Y_S = P'_{hot}/P_{cold}$  (see the inset in Fig. 1), with  $P'_{hot}$  the hot load output power at the same bias current as  $P_{cold}$ . This in contrast with the *conventional*  $Y$  factor defined as  $Y = P_{hot}/P_{cold}$  (inset in Fig. 1). From the figure it is obvious that  $Y_S > Y$ , indicating that the direct detection effect reduces the measured  $Y$  factor, increasing the apparent noise temperature.<sup>9–13</sup> A detailed study on the magnitude of the direct detection effect using a small volume NbN phonon cooled HEB mixer at a LO frequency of 1.6 THz has been discussed in Ref. 13. It was found that the noise temperature  $T_N$  obtained from a standard  $Y$  factor measurement is 35% lower than the small signal noise temperature  $T_{N,S}$  obtained using  $Y_S$ . From Ref. 13, and the discussion above related to Fig. 1 we can conclude that the combination of the bias current shift and the current dependence of the receiver output power (with a constant input power) is responsible for the direct detection effect. The output power of the HEB mixer with a thermal load with temperature  $T_{in}$  at its input is given by

$$P_{out} = Gk_B(T_{in} + T_N), \quad (1)$$

with  $G$  the mixer conversion gain,  $k_B$  Boltzmann's constant, and  $T_N$  the mixer noise temperature.<sup>15</sup> At fixed bias voltage the bias current dependence of the gain is in general stronger than the bias current dependence of the quantity  $(T_{in} + T_N)$  (as will be shown for our device at the end of Sec. III A), hence the bias current dependence of the mixer gain is expected to dominate the current dependence of the mixer output power. From a hot spot model description of the HEB mixer it is

known that the *mixer* gain decreases with increasing LO power.<sup>16</sup> However, this implies that the direct detection effect will always reduce the measured  $Y$  factor, since  $I_{DD}$  is always negative.<sup>9–13</sup> This is in agreement with results reported in Refs. 10–13, but in disagreement with the increase in  $Y$  factor due to the direct detection effect reported in Ref. 9. Possibly, this might be related to a change in IF match between the HEB mixer and the first amplifier due to the bias current shift associated with the direct detection effect. This is because a change in mixer bias current also results in a slight change in HEB complex impedance, which changes the IF match.

In this paper we describe a set of dedicated experiments in which we measure directly the change in receiver gain and the change in mixer IF match due to the direct detection effect. These experiments enable to understand which process is the principal cause of the direct detection effect. Furthermore we describe an experiment in which we measure the small signal noise temperature. The result of this measurement is compared to the change in receiver gain due to the direct detection effect.

## II. MEASUREMENT TECHNIQUE

As stated in the previous section we wish to measure directly how the direct detection effect influences the receiver gain, mixer gain, and mixer IF match. We also want to be able to compare the results with a direct measurement of the small signal noise temperature as performed in Ref. 13. This is achieved by the setup depicted in Fig. 2. It represents a fully automated  $Y$  factor measurement setup, in which the mixer bias voltage, LO power, and hot/cold load are all computer controlled. We can add an “RF signal” in the LO path or an “IF signal” in the IF chain, to be discussed below. As LO source we use a 673 GHz phase locked multiplier chain driven by a Gunn oscillator.<sup>17</sup> This signal is coupled reflectively by means of a 6  $\mu\text{m}$  Mylar beam splitter to the high density poly-ethylene (HDPE) cryostat window. After the window we have one Zytex G104 heat filter at 4.2 K and a simple mixerblock holding an elliptical Si lens with the Si HEB chip glued to its back. The HEB is made using a  $\sim 4$  nm NbN film and the NbN bridge is 1  $\mu\text{m}$  wide and 300 nm long. The critical temperature of the device is 9.5 K. The LO power requirement of this mixer is estimated to be 50 nW using the isothermal technique.<sup>18</sup> Radiation is coupled by means of a twin slot antenna with a center frequency of 650 GHz and an integrated bandwidth of 410 GHz, which is calculated by integrating the measured direct antenna response obtained using a Fourier transform spectrometer.<sup>17</sup> The total power difference between the hot and cold load at the mixer is estimated to be 0.9 nW, taken into account 1.75 dB of losses due to the optics and the calculated antenna efficiency. The mixer has a normal state resistance at 15 K of 170  $\Omega$  and a critical current at 4.2 K of 80  $\mu\text{A}$ . The IF output of the mixer is connected to a bias  $T$ , a directional coupler, and a Berkshire 1–2 GHz isolator and GaAs based low noise amplifier (4 K noise temperature, 40 dB gain). Outside the cryostat further amplification is performed using a commercial Miteq amplifier, subsequently

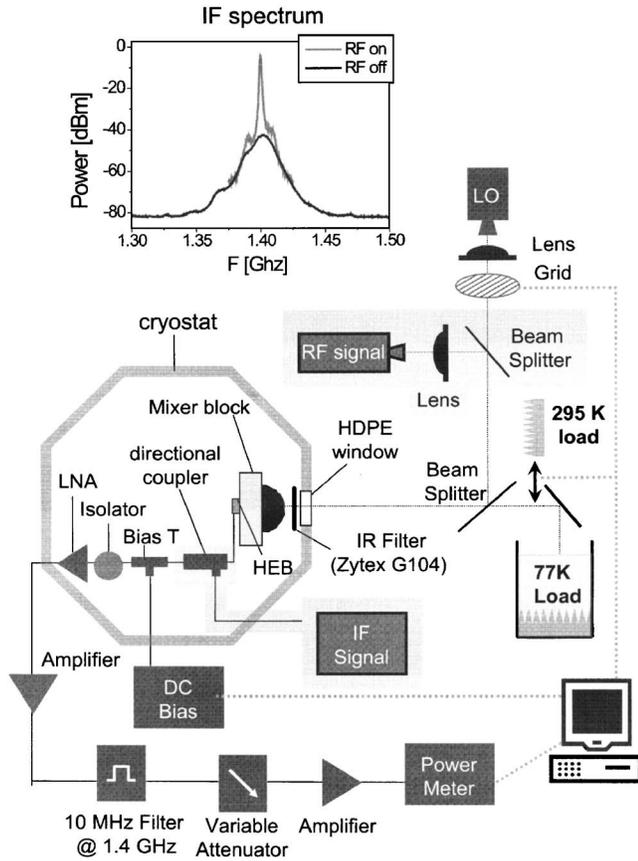


FIG. 2. Schematic picture of the experimental setup. The graph indicates the measured IF power spectrum after the last IF amplifier. The black line is the situation with both the RF and IF signal switched off. The gray line the situation with the RF signal switched on. The situation with the IF signal on is identical.

the signal is filtered in a narrow 10 MHz band around 1.40 GHz and sent through an attenuator and a final amplifier before it is detected in a broad band HP power meter. The attenuator is used to prevent saturation of the last amplifier.

To be able to measure the change in mixer gain due to the direct detection effect *alone* we add a continuous wave signal at a frequency of 1.40 GHz above the LO frequency to the LO path of the receiver. This is done by switching on the RF signal as indicated in Fig. 2. The RF signal is generated by another multiplier chain driven by a commercial synthesizer, locked to the phase locked loop of the LO source. The IF signal power, measured with the power meter, is 30 dB higher than the power measured with the RF signal switched off. This is partly due to the very narrow bandwidth set by the 10 MHz filter. Hence the power measured by the power meter is the mixing product of the LO and RF power. The mixing product of the LO and hot/cold load power is so much lower in power in the IF signal that it is not detected. This is illustrated in the plot in Fig. 2, where we show the IF spectrum as seen by the power meter measured using a spectrum analyzer, with and without the RF signal switched on. Care is taken to be sure that the RF signal power is still low enough to prevent any HEB bias current shift. Moreover, the (load temperature independent) high signal power of the RF signal makes sure that  $T_{in} \gg T_N$ , which shows, using Eq. (1), that the output power is now a direct measurement of the

relative receiver gain. Switching from hot to cold load enables us therefore to directly measure the change in HEB output power and thus the change in HEB receiver gain due to the direct detection effect alone. The  $Y$  factor in this experiment can thus be interpreted as the direct detection  $Y$  factor. Subtracting the direct detection  $Y$  factor from the conventional  $Y$  factor, obtained *without* the RF signal switched on, should give us the  $Y$  factor corrected for the direct detection effect. From this corrected  $Y$  factor we obtain the noise temperature corrected for the direct detection effect,  $T_{N,corr}$ , using the Callen and Welton definition.<sup>8</sup>

To measure the mixer IF match directly we switch off the RF signal and switch on the IF signal, shown in the lower shaded area in Fig. 2. The IF signal is a 1.4 GHz signal, generated by means of a commercial synthesizer. This signal is sent to the HEB chip by means of a  $-20$  dB directional coupler. This signal then reflects off the mixer and propagates through the IF chain. The power of the IF signal is again chosen to be low enough to prevent any measurable shift in mixer bias current. The signal measured at the end of the IF chain is now similar to the situation with the RF signal switched on described above, with a peak power again about 30 dB above the noise. It represents the total power reflected off the HEB mixer. We can normalize the reflection assuming that the mixer behaves as a perfect short when it is in its superconducting state at  $V=0$  and  $I=0$  without LO power applied. The normalized reflection  $R$  off the mixer is related to the IF match  $T$  according to  $T=1-R$ .<sup>19</sup> The change in match between the hot and cold load gives the IF match change due to direct detection. If we would know the direct detection effect due to the IF match and due to the receiver gain we can obtain the direct detection effect due to the mixer gain, by simply subtracting the IF match effect from the receiver gain effect.

As a last experiment we obtain the small signal  $Y$  factor  $Y_S$  by measuring simultaneously  $P_{hot}$ ,  $P_{cold}$ ,  $I_{hot}$  and  $I_{cold}$  as a function of bias voltage and LO power, without the use of either RF or IF signals. By constructing, after the measurement, a two-dimensional (2D) interpolation function of the mixer output power at hot and cold load as function of bias voltage and bias current, we can obtain the  $Y_S$  around either a 77 or 300 K background. This method is the 2D analog to the technique described in Fig. 1, and identical to the experiment discussed in Ref. 13. It corresponds to measuring the  $Y$  factor at constant bias current, obtained by slightly reducing the LO power at hot load to obtain the hot load output power at exactly the same bias current as at cold load. From  $Y_S$  we obtain  $T_{N,S}$  using the Callen and Welton definition.

### III. EXPERIMENTS

#### A. Measurement of noise temperature

In the first experiment we measure the conventional noise temperature  $T_N$  by means of measuring  $I_{cold}$ ,  $P_{hot}$ , and  $P_{cold}$  for all possible values of the bias voltage and applied LO power, without the use of either RF or IF signals. The noise temperature is obtained from  $Y=P_{hot}/P_{cold}$  using the Callen and Welton definition.<sup>8</sup> The measured values of  $T_N$  and  $Y$  are shown in Fig. 3 as a function of bias voltage and

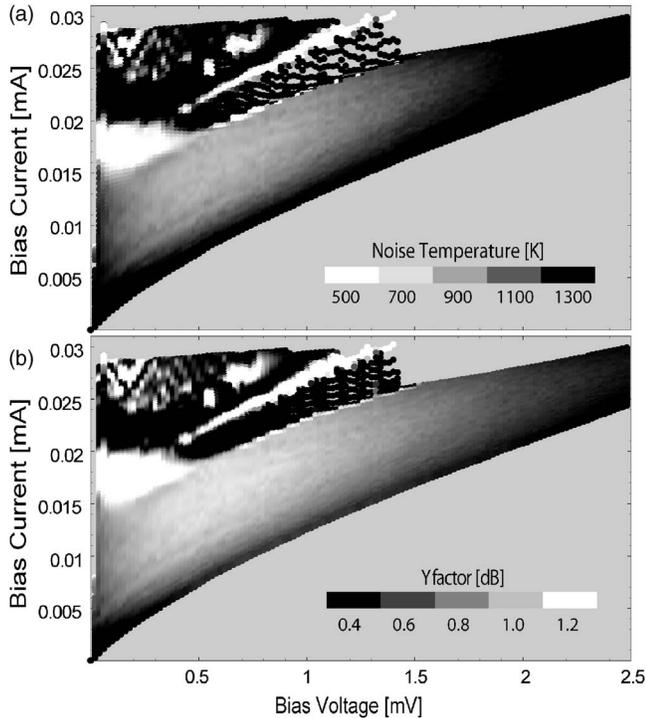


FIG. 3. (a) The (conventional) double sideband receiver noise temperature  $T_N$ , obtained from the  $Y$  factor shown in panel (b), for all bias points of the mixer, uncorrected for any optics losses. The minimum noise temperature is given by  $T_N=650$  K. (b) The measured (conventional)  $Y$  factor, defined as  $Y=P_{\text{hot}}/P_{\text{cold}}$  as shown in Fig. 1, obtained using 300 and 77 K blackbody calibration loads.

bias current.<sup>20</sup> We observe a broad optimal region with an optimal noise temperature of about 650 K. The small region at very low bias voltages around 0.017 mA seems to have an even lower noise temperature, but this will later be proven to be an artifact caused by the direct detection effect. We also observe that around the optimal bias voltage the bias current dependence of the mixer gain is stronger than the bias current dependence of the quantity  $(T_{\text{in}}+T_N)$ , which is identical to the bias current dependence of  $T_N$ , since  $T_{\text{in}}$  is not a function of bias current. Measurements are shown in Fig. 4 where we give  $G$  and  $T_N$  at three (constant) bias voltages around the optimum operating point as a function of the bias current. Note that this result implies that the current dependence of the mixer output noise at constant bias voltage, given by  $GT_N$ , is dominated by the gain current dependence, which is in agreement with Ref. 16. As a result the bias current dependence of the gain together with the bias current shift are the dominant ingredients in the direct detection effect.

## B. Measurement of the receiver gain dependence

We measure the direct detection  $Y$  factor, which is identical to the receiver gain change due to the direct detection (see Sec. II), by switching on the RF signal (see Fig. 2) and increasing the attenuation before the final amplifier by 30 dB. The measured direct detection  $Y$  factor, as a function of bias current and bias voltage, is shown in Fig. 5(a). We observe a negative direct detection  $Y$  factor for almost all bias points, indicating that the direct detection  $Y$  factor has a sign opposite to the normal  $Y$  factor. The only exception is

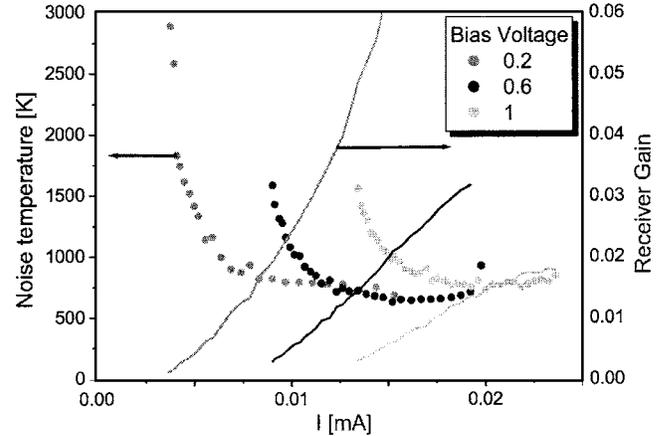


FIG. 4. Mixer input noise temperature  $T_N$  and receiver gain for three different bias points around the optimal bias voltage. From the figure and Eq. (1) it is clear that the bias current dependence of the gain is stronger than the bias current dependence of  $T_N$ . Hence, the bias current change due to direct detection causes predominantly a change in the gain when switching between loads, and (much) smaller change in mixer noise.

the very low bias region around 0.017 mA. To obtain the  $Y$  factor corrected for the direct detection effect, we subtract the direct detection  $Y$  factor [Fig. 5(a)], from the normal  $Y$  factor (with the RF signal switched off) as shown in Fig. 3(b). The corrected noise temperature obtained from this  $Y$  factor  $T_{N,\text{Corr}}$  is given in Fig. 5(b). We find a minimum value of  $T_{N,\text{Corr}}=520$  K, which is 20% lower than the minimum value of  $T_N=650$  K shown in Fig. 3(a). We also observe that

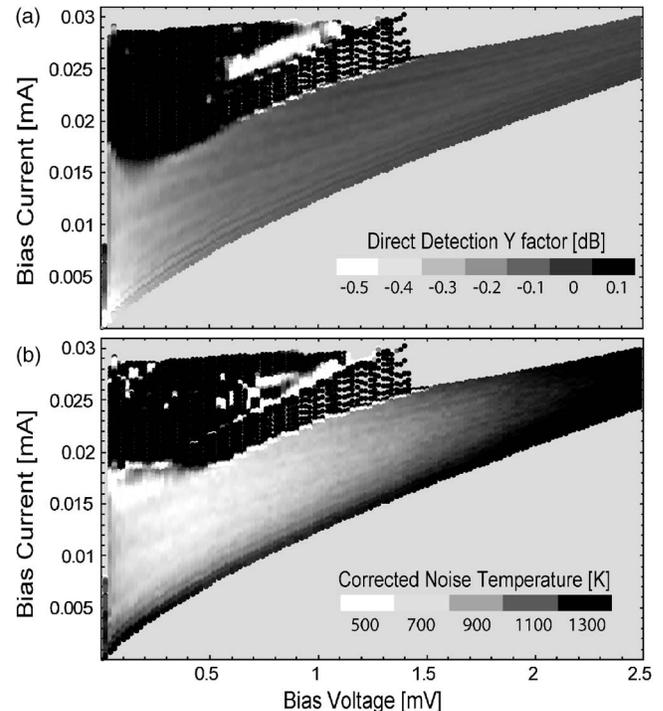


FIG. 5. (a) The direct detection  $Y$  factor, which is obtained with the RF signal switched on (see Fig. 2). Note that this  $Y$  factor represents the receiver gain change due to the bias current shift caused by the direct detection effect when switching between calibration loads. (b) Noise temperature corrected for the receiver gain change due to the direct detection effect. It is obtained from subtracting the direct detection  $Y$  factor [shown in panel (a)] from the conventional  $Y$  factor [shown in Fig. 3(b)].

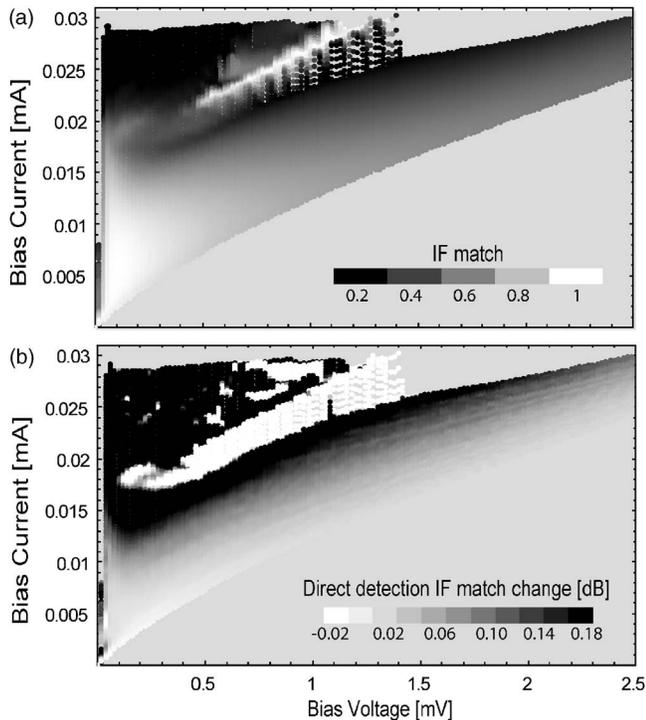


FIG. 6. (a) IF match of the HEB to the first amplifier of the IF circuit, obtained with the IF signal switched on as shown in Fig. 2(b) Change in the IF match (expressed as a  $Y$  factor in decibels) when switching from a hot to a cold load.

the location of the minimum in the noise temperature is shifted to lower bias voltages and that the small region with an apparent high sensitivity at low bias voltages and 0.017 mA, clearly visible in Fig. 3(a), has disappeared. These results are in agreement with the reduction in noise temperature due to the direct detection effect as reported in Refs. 9–13.

### C. Measurement of the IF match

To be able to measure the IF match, we switch off the RF signal and switch on the IF signal (see Sec. II). We measure  $P_{\text{cold}}$  and  $I_{\text{cold}}$  as a function of bias current and bias voltage and calculate the IF match as a function of bias current and voltage; the result is shown in Fig. 6(a). A similar result can be obtained from the measurement of  $P_{\text{hot}}$  and  $I_{\text{hot}}$ . We obtain a maximum match of 1, indicating that our normalization routine is to first order correct, and a region of optimal match at low bias currents and voltages. This is in agreement with direct measurements of the complex impedance of a similar HEB mixer with a similar normal state resistance as a function of the IF frequency,<sup>21</sup> where an impedance close to  $50 \Omega$  was found only at very low bias currents. Furthermore we observe that the match decreases almost monotonically (except for the lowest bias currents) with increasing bias current. Note that the mixer gain in general *increases* with increasing bias current. The change in IF match when switching from hot to cold load can be obtained from the combination of the measurements of  $P_{\text{hot}}$ ,  $I_{\text{hot}}$ ,  $P_{\text{cold}}$ , and  $I_{\text{cold}}$ . The result is shown in Fig. 6(b). Comparing Figs. 5(a) and 6(b), which represent the correction on the normal  $Y$  factor due to the receiver gain and mixer IF match, respec-

tively, we see a few striking differences: In the IF match experiment [Fig. 6(b)] the  $Y$  factor is mostly positive but has also a small negative component at very low bias currents. Hence the IF match changes in such a way due to the direct detection that it *increases* the apparent sensitivity of the HEB, except at very low bias currents. This in contrast to the effect that the direct detection has on the receiver gain as shown in Fig. 5. Since the effect of the receiver gain is the sum of the mixer gain and the IF match we must conclude that the direct detection effect on the *mixer* gain is even stronger than the effect on the *receiver* gain as shown in Fig. 5. It is to be expected that a different first stage amplifier or isolator or the use of a mixer with a different (complex) impedance changes the effect on the IF match. Note that the HEB complex impedance is a function of the normal state resistance of the device and the IF frequency. This would explain the results reported in Ref. 9, where a direct detection effect is observed that *decreases* the noise temperature, instead of the increase reported in Refs. 10–13. The decrease in noise temperature in Ref. 9 is in agreement with the IF match effect measured here.

### D. Measurement of the small signal noise temperature

We obtain the noise temperature in the small signal limit  $T_{N,S}$  by measuring  $P_{\text{hot}}$ ,  $P_{\text{cold}}$ ,  $I_{\text{hot}}$ , and  $I_{\text{cold}}$  at all possible bias points without the use of either the IF signal or the RF signal. From these data we obtain the direct detection current  $I_{\text{DD}}$  directly and  $Y_S$  around the 77 K load by constructing a 2D function of the output power at hot load by using interpolation of the original data, as described in detail in Sec. II and Ref. 13.  $T_{N,S}$  is obtained from  $Y_S$  using the Callen and Welton definition. The measured direct detection current is shown in Fig. 7(a). The direct detection current is always negative as expected and ranges from  $-1 \mu\text{A}$  at very low bias voltages to about 300 nA at the optimal operating region. These values are significantly lower than the ones reported in Ref. 13 for a similar mixer with a 1.6 THz antenna. The reason is the smaller bandwidth of the 650 GHz antenna compared to the 1.6 THz antenna used in Ref. 13. Note that the power difference between hot and cold load within the HEB antenna bandwidth, calculated to be 0.9 nW, is a small fraction of the total LO power (50 nW absorbed in the bridge). The noise temperature in the small signal limit around the 77 K load is shown in Fig. 7(b). We find that a minimum value of  $T_{N,S} = 520 \text{ K}$ , which is 20% lower than the minimum value of  $T_N = 650 \text{ K}$  shown in Fig. 3(a). We also observe that the location of the minimum in the noise temperature is shifted to lower bias voltages and that the small region with an apparent high sensitivity at low bias voltages and 0.017 mA, clearly visible in Fig. 3(a), has disappeared. Evaluating the small signal noise temperature at a background power level identical to the 300 K load, which can be obtained in a similar way, gives an identical result. Note that the sensitivity difference between  $T_N$  and  $T_{N,S}$  is here smaller than observed in Ref. 13, caused by the smaller integrated antenna bandwidth in the 650 GHz device measured here. When comparing the small signal noise temperature [Fig. 7(b)] with the noise temperature corrected for the direct detection effect on

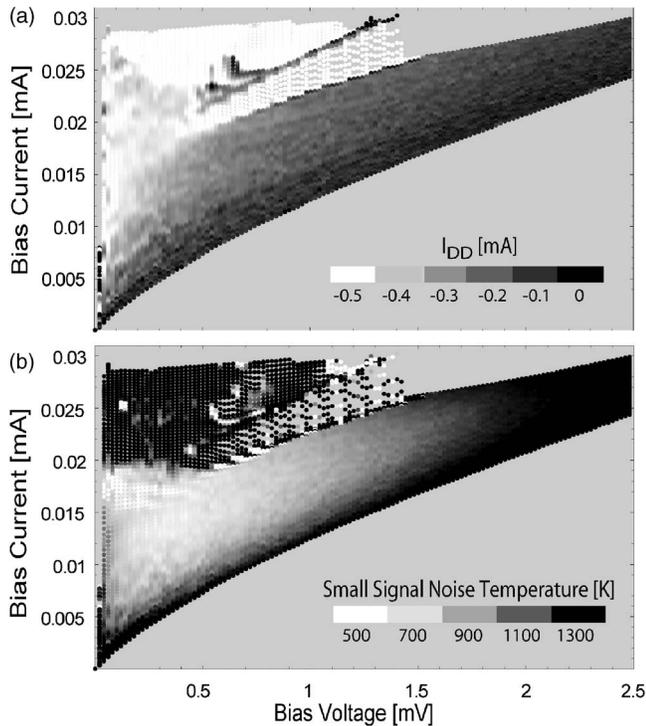


FIG. 7. (a) The direct detection current,  $I_{DD}=I_{hot}-I_{cold}$ . (b) The double side-band receiver noise temperature in the small signal limit,  $T_{N,S}$ , around a background corresponding to the 77 K load. This noise temperature corresponds to the noise temperature obtained from the small signal  $Y$  factor  $Y'=P'_{hot}/P_{cold}$  (see Fig. 1). The minimum value is  $T_{N,S}=520$  K. A background corresponding to the 300 K load gives an identical result.

the receiver gain (Fig. 5) we see that both are similar, as expected. The remaining differences are largely related to the bias current dependence of the mixer output noise, as illustrated in Fig. 4.

#### IV. CONCLUSION

We have measured the direct detection effect in a small volume, phonon cooled HEB mixer coupled to a 650 GHz twin slot antenna at 673 GHz. The direct detection effect manifests itself as a bias current reduction when going from a cold load to hot load in a  $Y$  factor measurement. This bias current reduction is caused by the increase in time averaged electron temperature in the bridge due to the increase in RF power over the entire antenna bandwidth of the mixer upon switching to a hot calibration load. As a result the magnitude of the effect is a function of antenna bandwidth and optical transparency and hot/cold load temperature difference. The consequence is that the hot load output power of the receiver is evaluated at a lower bias current than the output power at cold load. In an astronomical observation the total integrated power of the signal compared to the background is in general so small that the direct detection effect is negligible. The small signal noise temperature, in the absence of a direct detection effect, is found to be 20% lower (520 K) than the conventional noise temperature (650 K). We also observe a shift to lower bias voltages of the optimal operating point. In a separate set of experiments we measure the gain change due to the direct detection effect directly using an additional RF source. These two measurements together imply that it is

the receiver gain current dependence, together with the bias current shift when changing from a 300 to a 77 K load, that is responsible for the direct detection effect. In a separate experiment we measure the IF match. We find that the direct detection effect on the IF match is smaller and opposite in sign to the effect on the receiver gain. Since the receiver gain is the sum of the mixer gain and the IF match we conclude that the direct detection effect is mainly caused by the combination of the mixer bias current shift and the mixer gain current dependence. The effect of the IF match reduces the direct detection effect of the mixer gain. It is conceivable that the direct detection effect is a function of the amplifier that is used and of the (complex) impedance of the HEB mixer. The latter depends on the HEB normal state resistance but also on the IF frequency. When comparing these results with our results reported in Ref. 13 we see that the magnitude of the direct detection effect in Ref. 13 is larger, which is caused by the higher operating frequency and thus larger antenna bandwidth of the mixer. This shows that the magnitude of the direct detection effect depends strongly on the exact antenna bandwidth, LO power need, and optics of the instrument which makes the correct calibration of a (space based) heterodyne receiver that uses small volume HEB mixers problematic.

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- <sup>14</sup>The data is taken at the optimally pumped  $IV$  curve of the device discussed in Ref. 13.
- <sup>15</sup>Note that the current bias of the mixer in the presence of the direct detection effect is determined by the LO power *and* the load temperature. The usual approach that  $G$  and  $T_N$  are a function of LO power *alone* is no longer valid. Hence in the presence of the direct detection effect

$G=G(V,I)=G(V,[P_{LO},T_{load}])$  and  $T_N=T_N(V,[P_{LO},T_{load}])$ . This also implies that the definition of the  $Y$  factor is strictly speaking invalid in the presence of a direct detection effect since the  $Y$  factor definition requires that  $G_{hot}=G_{cold}$ . Hence only the small signal  $Y$  factor is a correct parameter, and the normal, conventional  $Y$  factor is not. This is due to the bias current change associated with the direct detection effect, which results in  $G_{hot} \neq G_{cold}$  because  $I_{hot} \neq I_{cold}$  and  $G$  depends on the bias current (which is a combination of LO power and load temperature). This is, however, a small effect that is ignored in the paper.

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<sup>20</sup>The bias current as shown in Figs. 3–6 is given by  $I_{hot}$ , which is chosen arbitrarily. Note however that  $I_{DD} \ll I_{hot}$ , so using  $I_{cold}$  in stead of  $I_{hot}$  would not change the graphs appreciably.

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