A Study of Direct Detection Effect on the Linearity of Hot Electron Bolometer Mixers

Yury V. Lobanov, Cheuk-yu E. Tong, Raymond Blundell, and Gregory N. Gol'tsman

Abstract— **We have performed a study of how direct detection affects the linearity and hence the calibration of an HEB mixer. Two types of waveguide HEB devices have been used: a 0.8 THz HEB mixer and a 1.0 THz HEB mixer which is ~5 times smaller than the former. Two independent experimental approaches were used. In the ΔG/G method, the conversion gain of the HEB mixer is first measured as a function of the bias current for a number of bias voltages. At each bias setting, we carefully measure the change in the operating current when the input loads are switched. From the measured data, we can derive the expected difference in gain between the hot and cold loads. In the second method (injection method [1]), the linearity of the HEB mixer is independently measured by injecting a modulated signal for different input load temperatures. The results of both approaches confirm that there is gain compression in the operation of HEB mixers. Based on the results of our measurements, we discuss the impact of direct detection effects on the operation of HEB mixers.**

Index Terms—**hot electron bolometer mixers, direct detection effect, conversion gain linearity.**

I. INTRODUCTION

SUPERCONDUCTING Hot Electron Bolometer (HEB) mixers have recently become the focus of active research in instrumentation for radio astronomy in the THz frequency band. Not only do HEB mixers exhibit good sensitivity in the THz regime (~10 times the quantum limit) [2]-[4], their Local Oscillator (LO) power requirements are low. This lends itself to operation with solid state sources. Earlier work on HEB mixers was mostly concentrated on noise performance and IF bandwidth. Now there is growing interest to study the direct detection response of HEB mixers and its effect on the linearity of its heterodyne response [2], [5]-[8].

It is well known that the bias current of an HEB mixer changes when its input port is switched between hot and cold loads. This phenomenon is commonly referred to as direct detection effect. Although HEB mixers are used mainly in heterodyne receivers, a direct detection response is always present because the incident black body radiation coming from the input load heats the electrons in the HEB element in the same way as the applied LO power. Given that the conversion gain of an HEB mixer is a function of its bias current, it is clear that the mixer gain will be different when its input port is switched between two very different temperatures. This non-linear behavior affects the accuracy of receiver calibration which in turn dictates the scientific usefulness of the receiver.

In this paper, we present our study of the linearity of HEB mixers. We demonstrate that the true noise temperature of an HEB mixer is lower than that computed from *linear Y-factor* measurements due to calibration error caused by direct detection effect.

In our experiments, we employ waveguide HEB mixers designed for 0.8 and 1.0 THz. These mixers were fabricated in the processing lab in Moscow State Pedagogical University. The details of the fabrication process and HEB characteristics have been reported elsewhere [3], [9]-[11]. For our waveguide HEB mixers, the superconducting NbN film (3.5 nm thick) is deposited on crystalline quartz substrate with an MgO buffer layer. Two different device sizes were used in our investigation, which helps us understand the impact of device volume on mixer linearity.

II. DIRECT DETECTION EFFECT

A. Mixer bias current

The direct detection response of an HEB mixer can readily be observed as a shift of bias current as the input load is switched between two very different temperatures. In Fig. 1a, an unpumped current – voltage characteristic (I-V curve) for an HEB mixer is displayed, together with an optimally pumped I-V curve. The latter is shown in greater detail in Fig. 1b from which we note that the pumped curve obtained with a cold (77 K) input load is different from that obtained with an ambient (295 K) input load. The bias current changes by ~ 0.1-0.4 μA near the low noise operating region marked in Fig. 1a as the input loads are switched between ambient and liquid nitrogen temperature, and $\Delta I/\Delta T_{input}$ is negative.

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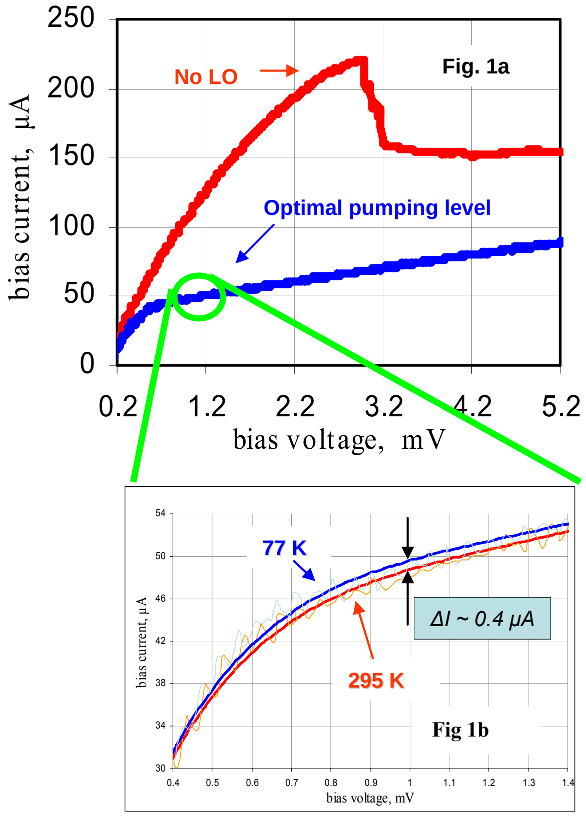

Fig. 1. Unpumped and optimally pumped I – V curves for the 0.8 THz HEB mixer under investigation. The low noise operating region is marked with a green circle (1a). Details of the I-V curves around the low noise region, show the mixer's response to different temperature input loads (1b).

In mathematical terms, the bias current in an HEB mixer, I_b, for an applied bias voltage, V_b, and applied local oscillator power, P_{LO}, can be written:

$$I_b = f(V_b, P_{LO}, P_{ext}) = I_{op}(V_b, P_{LO}) - S_I(V_b, P_{LO}) \cdot P_{ext} \qquad (1)$$

In this equation, P_{ext} is the incident signal power coming from a load placed at the receiver input and I_{op} is the nominal operating current set by the applied bias voltage and LO power in the absence of signal power. The second term of this equation represents the direct detection response of the mixer; S_I is the current responsivity of the mixer which is a function of the electron temperature in the HEB element and which in turn depends on the applied LO power P_{LO} and DC bias. Clearly, S_I increases with decreasing mixer volume because there are fewer electrons in the device. For our devices, S_I is estimated to be of the order of 100 A/W. The external incident signal power P_{ext} is given by

$$P_{ext} = k \cdot B_{Rx} \cdot T_{in}, \qquad (2)$$

where k is Boltzmann's constant, B_{Rx} is the receiver input bandwidth, and T_{in} is the input load temperature. In our experiment, B_{Rx} is around 0.3 THz and 0.5 THz for the 0.8 THz and 1.0 THz devices respectively. When we switch from an ambient to a liquid nitrogen cooled load, we have

$$\Delta P_{ext} = k \cdot B_{Rx} \cdot (T_{amb} - T_{cold}) \approx 1nW \cdot$$

This is not negligible when compared to the absorbed LO power. Thus, it is clear that the direct detection effect induced change in bias current, ΔI_b, will affect the operation of the mixer.

B. *Mixer output power*

The output power P_{out} of an HEB receiver can be written as:

$$P_{out} = 2 \cdot k \cdot B_{IF} \cdot G_R \cdot (T_{in} + T_{Rx}), \qquad (3)$$

where B_{IF} is the IF bandwidth, G_R is the mixer conversion gain and T_{Rx} is the receiver noise temperature.

It is well known that the conversion gain of an HEB mixer operating near its optimal low noise region is a monotonically increasing function of the bias current (hence, a monotonically decreasing function of LO power) [12]. This effect is illustrated schematically in Fig.2.

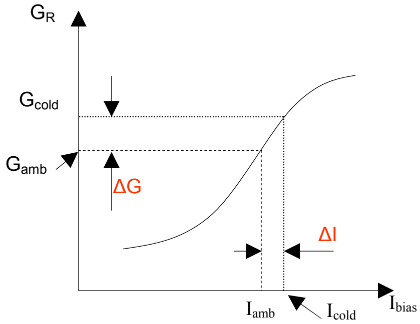

Fig. 2. Illustration of the dependence of mixer conversion gain as a function of the mixer bias current.

As a result of the bias current shift, the conversion gain for the cold input load is higher than that for the ambient load by ΔG. In terms of the measured Y-factor Y^{meas}, we have the following expression:

$$Y^{meas} = \frac{P_{out}^{amb}}{P_{out}^{cold}} = \frac{G_R^{amb} \cdot (T_{amb} + T_{Rx})}{G_R^{cold} \cdot (T_{cold} + T_{Rx})}. \qquad (4)$$

Since G_R^{cold} is larger, the measured Y-factor is expected to be reduced for larger values of direct detection induced bias current shift.

III. EXPERIMENTAL METHODS

We have two different methods to evaluate the deviation from linearity caused by direct detection effect: the *ΔG/G method* and an *injected signal method*. In addition, two different types of devices have been used in our investigation.

A. *Device type*

Table I shows the parameters of the two different types of devices used in our study. Although the HEB elements were fabricated at different times, they are expected to have similar film thickness of about 3.5 nm. From Table I we note that the 1.0 THz device is about 5 times smaller than the 0.8 THz device. Therefore, we expect it to demonstrate more pronounced direct detection effects.

TABLE I HEB MIXERS CHARACTERISTICS

Frequency, THz	**Chip size, mm × µm × µm**	**Active element area, µm × µm**	**Room resis-tance, Ohm**	**Critical current, µA**
0.8	2 × 126 × 30	0.12 × 1.5	55	218
1.0	1.5 × 90 × 23	0.065 × 0.5	90	103

B. *ΔG/G method*

Using the substitution $G_R^{amb} = G_R^{cold} - \Delta G$ and writing G instead of G_R^{cold}, (4) can be rewritten:

$$Y^{meas} = Y^{linear} \cdot (1 - \frac{\Delta G}{G}), \qquad (5)$$

where Y^{linear} is the Y-factor corresponding to the mixer exhibiting no direct detection effect.

In this method, (5) is used to derive the error in Y-factor measurements due to direct detection effects. In order to obtain the value of *ΔG/G*, the following steps are taken. First, the relative receiver conversion gain *G* is estimated by making use of equation (3),

$$P_{out}^{amb} - P_{out}^{cold} = 2 \cdot k \cdot B_{IF} \cdot G \cdot [(T_{amb} - T_{cold}) - \frac{\Delta G}{G} \cdot (T_{amb} + T_{Rx})]. \qquad (6)$$

If $\Delta G/G < 0.02$, the term $(T_{amb}+T_{Rx})\cdot\Delta G/G$ is less than a few percents of $(T_{amb} - T_{cold})$ for $T_{Rx} \sim 500\ K$. By neglecting the second term in (6), we can write down an approximate expression for the normalized receiver gain G_n:

$$G_n = \frac{P_{oout}^{amb} - P_{out}^{cold}}{2 \cdot k \cdot B_{IF} (T_{amb} - T_{cold}).} \qquad (7)$$

G_n is readily measured as a function of bias current for a given bias voltage. The experimental data set $G_n(I_b)$ is then fitted with a second order polynomial:

$$G(I) = a \cdot I_b^2 + b \cdot I_b + c \qquad (8)$$

In Fig. 3. we plot one set of measured data of $G_n(I_b)$ against I_b together with the quadratic fit. Once the dependence of G on I_b is derived, ΔG is calculated as follows:

$$\Delta G = \frac{dG_n}{dI} \cdot \Delta I = (2 \cdot a \cdot I_b + b) \cdot \Delta I, \qquad (9)$$

The quantity *ΔI* is simply the difference between bias current under different load conditions: $\Delta I = I_b^{cold} - I_b^{amb}$ and was measured simultaneously with the gain measurement.

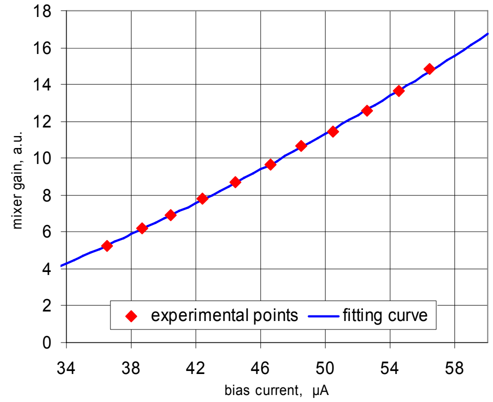

Fig. 3. Mixer normalized gain vs. mixer bias current: experimental data and for using (8).

In principle, the value of *ΔG* obtained from (9) can be fed back into (6) to increase the accuracy of the derived value of *ΔG/G*. However, we have not used an iterative approach in our study as *ΔG/G* is small.

The experimental set up for the *ΔG/G* method is the standard receiver Y-factor measurement set up (Fig. 4). In our cryostat, an isolator is used between the HEB mixer and the cold HEMT amplifier. It has been shown that the isolator helps mitigate unwanted effect caused by a mismatch between mixer and IF amplifier. This subject was not part of our study but has been covered by other researches, e.g. [6], [8]. The output IF signal from the cryostat is further amplified and filtered with a 2.7 GHz – 3.1 GHz bandpass filter. Finally, the IF output power is measured with a calibrated Agilent power meter. A computer controlled robotic arm carrying the ambient load, made from a square matrix of 3×3 Thomas Keating RAM tiles (25 mm square tile) [13], can swing periodically into the signal beam which is normally terminated by a 77 K cold load. *ΔI* and *ΔG* are measured simultaneously each time the loads are switched.

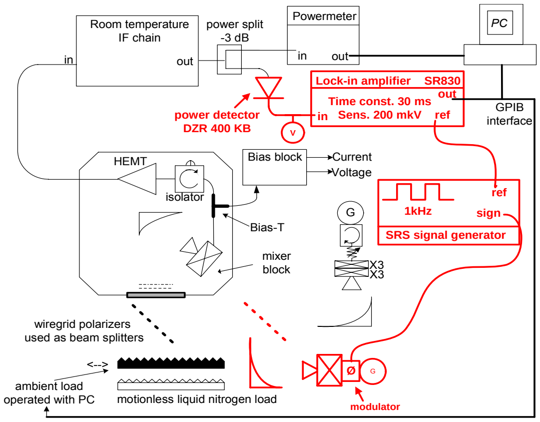

Fig. 4. Elements needed for the injected signal method (Lock-in amplifier, Power detector, SRS signal generator and modulated RF source) are shown in red. The room temperature IF chain consists of a cascade of amplifiers with a 2.7-3.1 GHz bandpass filter. The LO frequency is 0.810 THz.

C. Injected signal method

By injecting a weak signal at the receiver input port and recovery the same signal at the output port, we can derive the differential response of the receiver under its nominal operating conditions. This method has successfully been implemented for SIS mixer calibration [1], [14], [15]. Non-linear mixer conversion gain response can easily be observed by comparing the magnitudes of the injected signal at the receiver output under different input load temperatures with equal injected signals.

Referring to Fig. 4, an additional modulated RF signal source is coupled to the LO beam using an additional wire grid polarizer. The additional Gunn oscillator is modulated by a 1 kHz square wave (ON/OFF modulation) before driving a frequency multiplier to generate modulated radiation at 0.813 THz.

At the receiver output, the modulated signal is picked up by a power detector DZR 400 KB [16] followed by a lock-in amplifier. The detector is operated well-below saturation. A calibration procedure [1], [6] performed by injecting test signal into IF chain thru directional coupler does not show any deviation from linearity so long as detector voltage remains less than 4 mV. The voltage registered by the lock-in amplifier is set to be ~ 1% of the DC voltage measured by the detector.

The principle of the measurement is illustrated schematically in Fig. 5.

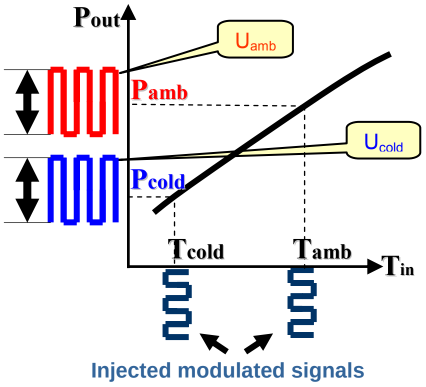

Fig. 5. Schematic representation of mixer output power vs. input load temperature. Modulated injected signals generate input power switching and the modulation created at the output depends on the slope of the P-T curve for a given input load temperature. U_{amb} and U_{cold} are voltages measured by the lock-in amplifier following for the power detector.

Let U_{amb} and U_{cold} be the voltages measured by the lock-in amplifier when the receiver is terminated by an ambient and a cold load respectively. For a perfectly linear mixer, U_{amb} and U_{cold} should be equal. In the presence of gain compression, U_{amb} and U_{cold} are no longer equal and any observed difference between them can be used to derive the mixer's gain non-linearity.

For small deviations from linearity ($\Delta G/G < 0.02$) the receiver output power as a function of input temperature can be written:

$$P(T_{in}) = P_0 + mT_{in} - \alpha T_{in}^2, \qquad (10)$$

for some coefficients m and α. Since the lock-in amplifier measures the differential changes of output power, the ratio between U_{amb} and U_{cold} is proportional to the slope of the $P(T)$ curves in (10) for $T = T_{amb}$ and T_{cold} respectively. This ratio, R, can be written down as:

$$R = \frac{U_{amb}}{U_{cold}} = \frac{\left.\frac{dP}{dT_{in}}\right|_{T_{amb}}}{\left.\frac{dP}{dT_{in}}\right|_{T_{cold}}} = \frac{m - 2\alpha T_{amb}}{m - 2\alpha T_{cold}}. \qquad (11)$$

Note that the quadratic term in (10) represents the mixer's deviation from linearity as a result of the mixer's direct detection response. The output power from a perfectly linear mixer would only contain the constant and linear terms: $P(T_{in}) = P_0 + mT_{in}$. The theoretical Y-factor for such a perfectly linear mixer with no direct detection effect Y^{linear} can be written:

$$Y^{linear} = \frac{P_0 + mT_{amb}}{P_0 + mT_{cold}} \qquad (12)$$

where the coefficients P_0 and m are solved from (11) and (10) for T_{amb} and T_{cold}.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

In the *ΔG/G method*, we measure values of ΔI_b for the 0.8 THz device ranging from 0.1 µA – 0.4 µA depending on the nominal bias current. In order to compare the significance of this bias current shift, ΔI_b has to be normalized by the nominal bias current I_b. Fig. 6 gives a plot of $\Delta I_b/I_b$ as a function of bias current.

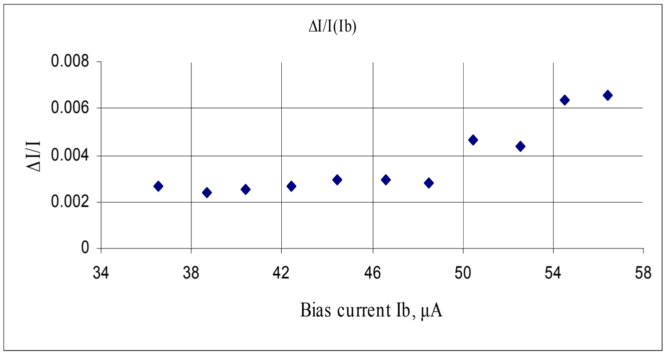

Fig. 6. $\Delta I_b/I_b$ vs. I_b for 0.8 THz receiver.

We note that the bias current shift caused by the direct detection effect is larger at higher bias current, where LO power is lower and conversion gain is higher. For the 1.0 THz device $\Delta I_b/I_b$ lies in this range of 0.4% – 0.8% versus 0.2% - 0.6% for the 0.8 THz device. The slightly higher value for the 1.0 THz device is most likely a result of its smaller size.

Compared with quasioptical HEB mixers which were studied in [2], [5], [6], [8], [10], [11] the value of $\Delta I_b/I_b$ registered by our waveguide HEB mixer tends to be smaller by about an order of magnitude. This difference is probably because of difference in input bandwidth which is usually much wider for quasioptical mixers.

For both 0.8 THz and 1.0 THz devices, the value of $\Delta G/G$ is less than 0.02. This verifies the validity of the approximate expression for receiver gain given by (7). As expected, $\Delta G/G$ is also larger in the case of the 1.0 THz mixer by a factor of 2-3.

In the *injected signal method,* the ratio of lock-in voltages lies between 1.008 and 1.014 for the 0.8 THz device and between 1.035 and 1.050 for the 1.0 THz device.

Receiver noise temperature is measured at the optimal operating voltage bias for the given HEB mixer (that is 1.0 mV for 0.8 THz receiver and 0.5 mV for 1.0 THz receiver) as a function of bias current I_b. First, Y-factor and bias current change ΔI_b are measured for each bias point and, then a modulated injection signal is introduced, U_{amb} and U_{cold} are measured. All measured values are statistically analyzed for experimental errors and measurement uncertainties. After that, corrected Y-factors determined by both methods by (5) and (12) are computed. The results for the 0.8 THz HEB mixer are given in Fig. 7. From the figure, the injection method yields a smaller correction to the measured Y-factor. Correction given by the *$\Delta G/G$ method* is larger and is more sensitive to the value of the bias current. In fact, the required correction is close to the accuracy of our Y-factor measurement, which is limited by receiver instability.

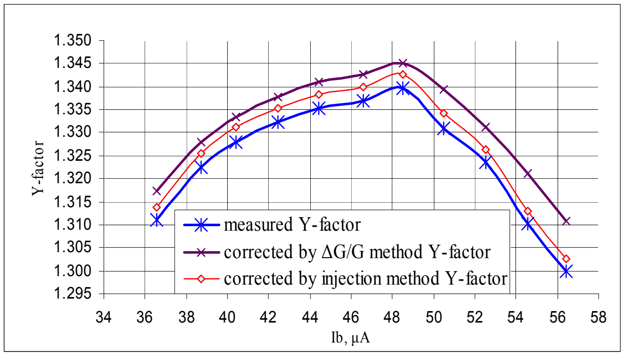

Fig. 7. Measured and corrected Y-factor vs. bias current I_b.

The results of our measurements in terms of receiver noise temperature are summarized in Table II for both 0.8 THz and 1.0 THz devices. Comparing the two methods, the percentage correction in noise temperature given by the injection method appears to show less scattering. This may be attributed to the larger error in the measurement of ΔI_b, resulting from receiver instability and noise in our measurement system. Both methods confirm that the use of smaller devices would lead to larger correction in the experimental Y-factor using ambient load.

TABLE II CORRECTED AND UNCORRECTED NOISE TEMPERATURE

Frequency, THz	**Bias current, µA**	**Measured noise temperature, K**	***$\Delta G/G$ method***		***Injection method***	
			Corrected noise temperature, K	**Correction in %**	**Corrected noise temperature, K**	**Correction in %**
0.8	36.5	624	610	2.23	618	0.98
	42.4	579	568	1.80	573	0.97
	48.5	565	555	1.73	559	0.99
	54.5	626	602	3.81	620	0.98
1.0	27.3	702	652	7.23	681	3.00
	28.1	723	680	5.94	692	4.26
	29.2	721	691	4.05	688	4.57

V. CONCLUSION

Direct detection response of the waveguide HEB mixers was observed experimentally and has been studied with both theoretical considerations and experiments. Two independent experimental methods were adopted for precise HEB mixer based receiver calibration which takes into account direct detection response of the HEB mixer.

Our experimental data demonstrate that direct detection effects produce calibration error which is less than 10% for receiver noise temperature calibration and less than 1% for receiver gain calibration.

As predicted, the smaller device volume is, the stronger is the observed direct detection effect. Clearly, when an HEB mixer is chosen for a certain task that requires very tight calibration standard, it may be necessary to employ either devices with larger volume or calibration load with a lower physical temperature instead of an ambient one. Alternatively, the use of our experimental methods can also allow a partial removal of the nonlinearity effect caused by gain compression.

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