Stabilization Scheme for Hot-Electron Bolometer Receivers Using Microwave Radiation

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***Abstract*—We present the results of a stabilization scheme for terahertz receivers based on NbN hot-electron bolometer (HEB) mixers that uses microwave radiation with a frequency much lower than the gap frequency of NbN to compensate for mixer current fluctuations. A feedback control loop, which actively controls the power level of the injected microwave radiation, has successfully been implemented to stabilize the operating point of the HEB mixer. This allows us to increase the receiver Allan time to 10 s and also improve the temperature resolution of the receiver by about 30% in the total power mode of operation.**

***Index Terms*—Allan variance, hot-electron bolometer (HEB) mixer, radiometer equation, terahertz receivers.**

I. INTRODUCTION

THE terahertz region of the electromagnetic spectrum is emerging as an important field for observational astronomy [1]–[4]. Certain processes in the life cycle of the interstellar medium, in the Milky Way and other galaxies have signature emission or absorption lines at terahertz frequencies. Molecular species such as CO, CS, SO, SO_2, HCO^+, HCN, C, N^+, and C^+ can all be observed in this part of the electromagnetic spectrum. Hence, observations performed in the terahertz region may provide deeper understanding of the phenomena which take place inside giant interstellar molecular clouds and star formation regions, as well as information about various processes occurring in the Milky Way and in other galaxies.

The hot-electron bolometer (HEB) mixer has been established as the detector of choice for astronomy at terahertz frequencies because of its low noise temperature (typically 1 K/GHz), relatively wide intermediate frequency (IF) bandwidth [5]–[9], and also because it requires much less local oscillator (LO) power than competing Schottky diode mixers [10]–[12]. Below about 1 THz, SIS mixers are widely used in radio-telescope receivers because of their quantum-limited noise performance and their stability with respect to LO power fluctuations during operation. Above 1 THz, however, the performance of SIS receivers deteriorates due to the band gap effect [13]. That is why in the Heterodyne Instrument for the Far-Infrared (HIFI) to be launched on board the Herschel spacecraft, an HEB-mixer-based receiver will be used for Band 6 (1410–1910 GHz) .[1]

In the early days of development of receivers for radio-astronomy, most of the research was focussed on realizing low noise temperatures. However, for the observation of most astronomical objects at terahertz frequencies, the low noise requirement is often not sufficient to guarantee that the magnitude of the received astronomical signal, usually expressed in terms of an equivalent blackbody radiation temperature, can be determined to the desired resolution ΔT. This temperature resolution of a particular receiver is dictated in part by its stability. It is commonly accepted that an HEB receiver has a poorer stability than an SIS receiver [14], [15]. In this paper, starting from a simple empirical fluctuation model of an HEB receiver, we will present improvements to the stability of the receiver by implementing a microwave feedback loop. The purpose of the controlled microwave injection is to counteract variations of the LO drive and thus stabilize the performance of an HEB receiver. This microwave injection scheme has been used successfully to improve the stability and temperature resolution of an HEB receiver operating at 0.8 THz.

II. FLUCTUATION MODEL

In principle, to facilitate the reception of a very weak signal, the desired signal-to-noise ratio can be achieved by simply increasing the integration time. The relationship between the integration time and the temperature resolution of a radio receiver is given by the radiometer equation [16]

$$\Delta T = \frac{T_{\rm sys}}{\sqrt{B\tau}} \equiv \frac{T_R + T_A}{\sqrt{B\tau}} \tag{1}$$

where $T_{\rm sys}$ is the system noise temperature, which is equal to the sum of the receiver noise temperature (T_R) and the antenna temperature (T_A), B is the receiver final detection bandwidth, and τ is the integration time. However, (1) is valid provided that (a) the incoming signal presents white noise and (b) the parameters of the radiometer are constant. In reality, (b) does not hold because receivers always present some elements of instability. Consequently, the output of the receiver can be viewed as the sum of two random variables: one associated with the incoming signal, which is assumed to follow white noise statistics, and the other depending on the fluctuating parameters of the receiver itself. Equation (1) can, therefore, be rewritten

$$\left(\frac{\Delta T}{T_{\rm sys}}\right)^2 = \frac{1}{B\tau} + f(\tau) \tag{2}$$

Manuscript received July 21, 2008; revised October 20, 2008. First published December 12, 2008; current version published January 28, 2009. This paper was recommended by Associate Editor J. Mazierska.

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Digital Object Identifier 10.1109/TASC.2008.2008398

[1] [Online]. Available: http://herschel.jpl.nasa.gov/hifiInstrument.shtml

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where $f(\tau)$ is some function of the integration time τ. Measurements on operating radiometers show that $f(\tau)$ can be approximated by the sum of a constant term and a term proportional to τ^z with $1 < z < 2$ [17]. By adopting this fluctuation model, we can derive an equation for the temperature resolution of a radiometer

$$\Delta T = T_{\text{sys}} \sqrt{\frac{1}{B\tau} + \alpha + \beta \tau^z}. \tag{3}$$

The parameters α and β of the fluctuation model are to be determined experimentally and represent $1/f$-noise and drift noise, respectively [18]. While the $1/f$ noise is well known to be associated with all electronic processes, the drift noise component, as described by the third term in (3), is associated with thermal processes. Clearly, thermal drift noise occurring over long timescales will not be affected by the averaging procedure and will result in the increase of the standard deviation of the output signal and the degradation of the receiver temperature resolution.

Equation (3) provides a method to estimate the optimum integration time of a receiver. A simple plot of $(\Delta T/T_{\text{sys}})^2$ versus integration time τ yields a minimum at the crossover point below which white noise dominates, but above which $1/f$ noise and drift noise are dominant. This procedure was first introduced by Allan in 1966 [19], and the plot itself is called *the Allan variance* plot. The time corresponding to the minimum of $(\Delta T/T_{\text{sys}})^2$ is referred to as *the Allan time*, integrating beyond which will not improve the temperature resolution of a receiver. Although in the absence of $1/f$ noise this transition is quite sharp, most Allan variance plots present a broad valley, seldom with a well-defined minimum.

When a radiometer is used to determine the equivalent blackbody radiation of a source over a wide frequency range, typically $B > 0.01 f_{\text{sig}}$, the usual procedure is to switch the input of the receiver between the source and a reference blackbody ideally at a temperature close to the antenna temperature of the source. Thus, some fraction of the observational time, optimally one half, is spent on calibrating the receiver [20], [21]. The switching can be done, for example, by scanning the antenna or by using a nutating secondary mirror or a chopper. In any setup, there is some "dead time" between the two switched positions. In the case of mechanically moving the entire antenna, the unproductive time may be several seconds [22]. Clearly, for an efficient observation, the radiometer needs to dwell on the source or calibrator for a period that is much longer than the "dead time." If the Allan time is of the same order as the unproductive time, the observation becomes highly inefficient and will not result in the highest possible temperature resolution allowed by (3). In the case of a nutating mirror or chopper, the dead time can be much shorter, and the switched observation may be made quite efficiently. Thus, the optimum integration time is determined by (a) the upper limit of the temperature resolution of the receiver, which is to say, its maximum acceptable value; and (b) the switching rate, and hence the dead time of the receiver.

Recent experiments with HEB receivers show Allan times of typically 1 s [17], which is obviously too short for efficient observation with most calibration schemes involving mechanical movement of large structures.

Among the factors that contribute to the drift in the output of an HEB receiver, the most prominent one is the variation of the IF output power as a function of incident LO power. Unlike the case of SIS receivers, which are often operated at a saturated LO drive at which the IF output is insensitive to LO power fluctuations, the IF output of an HEB receiver tuned for the lowest noise temperature is a sharp function of the LO drive. At higher drive levels, the receiver output becomes less sensitive to the LO drive. This occurs, however, at the expense of increased noise and degraded performance. One further issue is that abundant LO power is not always readily available in the terahertz regime, so HEB receivers are often operated with a highly tuned LO chain involving several cascaded varactor multipliers and a resonant LO injecting scheme, such as a Martin–Puplett interferometer.

Drift noise in an HEB receiver can, therefore, be readily observed and, to some extent, predicted by monitoring the bias current of the receiver. In order to reduce such LO-related drift effects, we have experimented with a microwave injection scheme designed to help maintain a constant bias current by adjusting the amount of coupled microwave radiation. The details of this scheme will be developed in the sections that follow.

III. HEB Devices

All experiments described below were performed at an LO frequency of 0.81 THz with waveguide HEB mixers. The mixer elements are fabricated on z-cut crystalline quartz substrates from 3.5-nm NbN films sputtered on top of 200 nm of MgO, which serves as a buffer layer to ensure good acoustic match and an increase in the IF bandwidth. The films are patterned using photo- and e-beam lithography to obtain bolometric elements typically 0.12–0.13 μm long and 1.5 μm wide. The substrates supporting the HEB elements are then lapped to a thickness of about 30 μm and diced into individual mixer chips 2 mm long and 126 μm wide. The HEB elements generally have transition temperatures of about 8 K with a transition width of 0.5 K, room-temperature resistances of about 60 Ω, and critical currents of typically 200 μA.

IV. Experimental Setup

A schematic of the experimental setup is shown in Fig. 1. The HEB mixer chip is installed into a half-height waveguide mixer-block mounted onto the cold plate of the liquid helium cryostat. A cascade of two solid-state frequency triplers, driven by a Gunn oscillator operating at 90 GHz, provide LO power at a frequency of 0.81 THz. The vacuum window of the cryostat is made of z-cut crystalline quartz ~2.7 mm thick, covered on both sides with low-density polyethylene ~60 μm thick. Signal input and LO drive are combined in a Martin–Puplett interferometer ahead of the vacuum window. They then pass through two Zitex G106 cold infrared filters, mounted on the 77-K radiation shield and the cold plate, respectively, and are coupled to the corrugated feed horn of the mixer-block via a focusing mirror mounted on the cold plate. The IF output from the mixer passes through a bias-tee, followed by a 2.5- to 4.0-GHz cryogenic circulator, and is then amplified by a low-noise cryogenic amplifier with a gain of 30 dB over the frequency range 3–8 GHz.

A room-temperature part of the IF chain consists of two amplifiers, each with a gain of 35 dB over the frequency range 1–6 GHz and separated by a 380-MHz bandpass filter centered

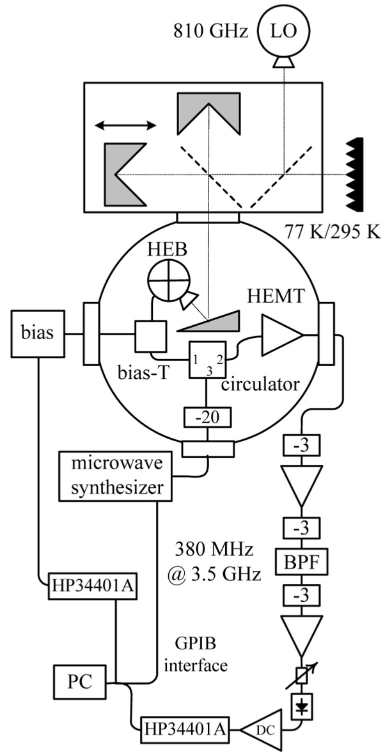

Fig. 1. Schematic of the experimental setup.

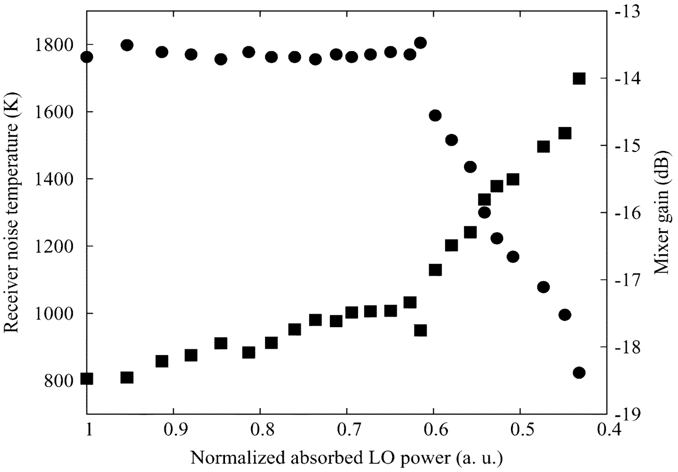

Fig. 2. Effect of microwave radiation on the HEB device. Starting from the optimal LO power (normalized absorbed LO power is unity) and zero injected microwave power, the LO power at 0.81 THz is gradually reduced. At each step of the reduction, the operating bias current is restored by injecting more microwave power at 17.3 GHz. In this plot, we record the receiver noise temperature (squares) and the mixer conversion gain (circles) as functions of the normalized absorbed LO power at 0.81 THz.

at 3.5 GHz, and is used to amplify the receiver output to the level required by the Agilent 8473D power detector which is set to operate in its linear regime using a tunable attenuator. The room-temperature components are enclosed in an aluminum box, which is bolted down to the optics bench to ensure good temperature stability. The signal from the power detector is fed to a dc instrumentation amplifier SR560 operating with a 10-Hz low-pass filter at a roll-off of 12 dB per octave and a set gain of 200. The output of the amplifier is connected to an HP34401A multimeter which is read remotely at a rate of about 65 Hz. Finally, another HP multimeter is used to measure the mixer current through a 15-Hz low-pass filter at the same sampling rate. The low-pass filters thus ensure that the sampled signals are not aliased [23].

The microwave injection scheme involves the coupling of microwave power at 17.3 GHz from an HP83630A synthesizer to the mixer through the third port of the cryogenic circulator. To reduce the noise from the synthesizer and to block the thermal power from the room background, a cold 20-dB attenuator is incorporated on the third port of the circulator. Output from the synthesizer is absorbed by the HEB element and is used to maintain the receiver current at the desired, set operating point. The choice of the injection frequency is dictated by several factors. First, this frequency should be much lower than the main LO frequency so as not to introduce any spurious tones at the receiver output. Second, for the same reason, it should be much higher than the mixer IF roll-off frequency, which is about 3 GHz for the NbN films used in these experiments. In addition, and simply for practical reasons, the frequency should be chosen such as to enable coupling through the circulator, which although is rated to operate at a few gigahertz, at much higher frequencies has additional modes that allow low-loss injection. Finally, the injection scheme should be as simple as possible. Considering all the above aspects, we set the injection frequency to 17.3 GHz.

V. MICROWAVE INJECTION

The details of the effect of microwave radiation on the performance of HEB mixers have already been reported previously [24]; here we summarize only the main results. Injection of microwave radiation with a frequency much lower than the gap frequency of the superconducting film, in this case NbN, generally results in a degradation of the receiver noise temperature and gain. However, so long as the relative change of the absorbed LO power is small, $<10\%$, substitution of microwave radiation for terahertz radiation does not significantly affect the conversion gain or the noise temperature of the receiver (see Fig. 2). Thus, it is possible to compensate for fluctuations of LO power by injecting microwave radiation. This is the main principle behind the feedback loop described here. It can be argued that it is more direct to servo the LO unit itself, but the current microwave injection scheme stands out as more universal, applicable to all sorts of LO sources, ranging from solid-state units, to backward-wave oscillators and even quantum cascade lasers. In addition, the implementation is extremely simple and versatile.

The role of the injected microwave radiation, at a frequency significantly below the gap frequency in the NbN film (estimated to be about 0.9 THz for the unheated film), is that it induces a high frequency current. The normal component of this current results in additional dissipation of energy, and consequently contributes to the heating of the sample. For low levels of injection ($<10\%$ of incident terahertz LO power), the injected microwave power basically modulates the electron temperature of the NbN film. Furthermore, since the chosen frequency is well above the IF roll-off frequency, the electron temperature will be modulated by the average value of the injected microwave power. Consequently, the injected microwave power

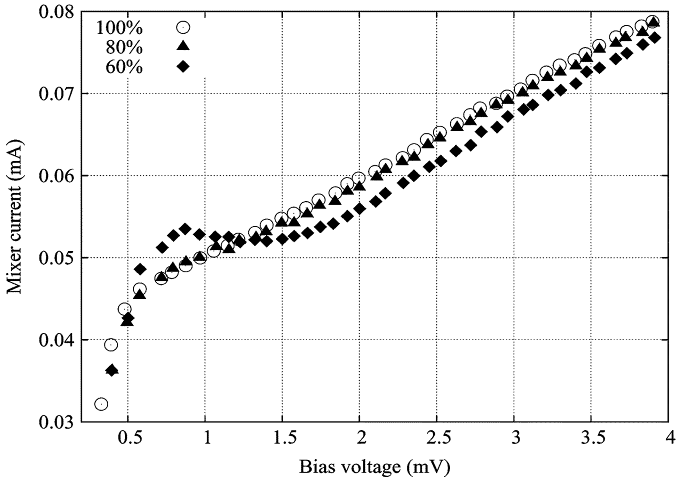

Fig. 3. Current–voltage characteristics of an HEB mixer pumped by a combination of LO power at 0.81 THz and injected microwave power at 17.3 GHz. The levels of LO power used are, respectively, 100% (circles), 80% (triangles), and 60% (diamond) of optimal LO power at 0.81 THz. The level of injected microwave power for the two cases of reduced LO drive is adjusted so as to maintain the low noise bias point of 1.2 mV and 0.052 mA.

can be effectively used to maintain a constant electron temperature in the NbN film.

Referring to Fig. 3, we observe that the shapes of the three pumped current voltage characteristics are different. If the injected microwave power had the same effect on the HEB mixer as the LO power at 0.81 THz, then the three curves would be identical. In order to understand this effect, we note that at the bias point for efficient mixer operation the electron temperature is close to the critical temperature of the film, and the energy gap is suppressed so that the LO frequency of 0.81 THz is greater than the gap frequency of the film and Cooper pairs are broken by the incident LO radiation. Nevertheless, the gap frequency of the NbN film is still far greater than that of the injected microwave signal of 17.3 GHz. For this reason, as the microwave signal is substituted for the 0.81-THz LO, the detailed shape of the pumped current–voltage curve of the HEB mixer element changes. One might succeed in explaining this phenomenon by looking more closely into what is actually going on in the film, specifically into the mechanism of the transition from the superconducting state to the normal state under these conditions. It may simply be the result of the Ginzburg–Landau depairing process. Alternatively, the phenomenon may be related to actions of vortices present in the film. Finally, the difference in the effects produced by the two frequencies may also be explained by the differences in the impedance of the film at these frequencies.

Although no definite conclusion about the microscopic effects of microwave radiation on the HEB device has been presented, we have successfully used an injected microwave signal to reduce gain instabilities in an operating HEB mixer via a simple feedback control loop. The details of its implementation will be described in Section VI.

VI. STABILITY MEASUREMENTS

In order to determine the stability of our working HEB mixer receiver, we first needed to measure that of the receiver IF system including the power detector, the dc amplifier, and the multimeter. For this purpose, we used a noise source[2] which provided white noise in the frequency range 0.01–3 GHz at the head of the room-temperature IF chain; the available noise power was about $+3$ dBm. By using a narrower bandpass filter and appropriate attenuator, we verified that the measured Allan variance demonstrated a dependence of $1/B\tau$, as given by the radiometer (1), up to the transition point between white noise and drift noise of around $\tau = 5$ s.

The stability of the receiver was then measured at the low-noise operating point (bias of 1 mV and 50 μA), which was found by using the standard Y-factor procedure.[3] A series of measurements were performed, with the feedback loop open and closed during alternative measurements in order to make a comparison with contiguous sets of data. For these experiments, the feedback control loop was implemented with the integral term only. With the feedback loop engaged, the level of microwave power at time t is adjusted as follows:

$$P(t) = P(0) - K \sum_{x=\tau}^{x=t} \left(I(x-\tau) - I_{\text{preset}}\right) \tag{4}$$

where $P(0)$ is the initial level of microwave power, usually around -5 dBm, $K = -0.1$ dB/μA, I_{preset} is the value of the mixer current at the low-noise operating point, and $1/\tau \approx 65$ Hz is the sampling rate.

If the frequency of the incident radiation is much lower than the energy gap of the superconductor, the current–voltage characteristics of an HEB mixer under RF signal will have a "kink," i.e., they will not be monotonous until RF power is so great as to drive the device almost normal. We noticed that current–voltage characteristics behave similarly when the LO drive at 0.81 THz is combined with microwave radiation at 17.3 GHz and the power level of the latter is too high. As a rule of thumb, we found that if the current–voltage characteristic of the HEB device does not have a region with a negative differential resistance (a "kink") when terahertz LO drive and the injected microwave signal are combined to bring the mixer to the chosen operating point, then the initial power level of microwave radiation is not too high (see Fig. 3). On the other hand, the power level of the injected microwave radiation should be sufficient to provide reserve for adjustment against any possible wild fluctuations of the mixer current during the experiment. The coefficient K in (4) is found experimentally by noting the change of the mixer current with respect to the change of microwave power. Initially K was set to -2 dB/μA. However, during subsequent experiments we found that a value of -0.1 dB/μA provided a better result. Fig. 4 shows the HEB mixer current versus time with the feedback loop open and closed. Also shown is the level of injected microwave power versus time. As can be seen, the use of the microwave feedback scheme allows complete stabilization of the receiver operating point.

Stability measurements of the entire IF chain, including the cold HEMT amplifier, are performed by setting the mixer bias voltage to zero and blocking the LO (to prevent any fluctuations

[2] We used a noise diode NW3G-D-TTL from Noisewave. [Online]. Available: http://www.noisewave.com

[3] When computing the receiver noise temperature, we used Planck's formula for blackbody radiation. For discussion of other approaches to this procedure, the reader may consult [25].

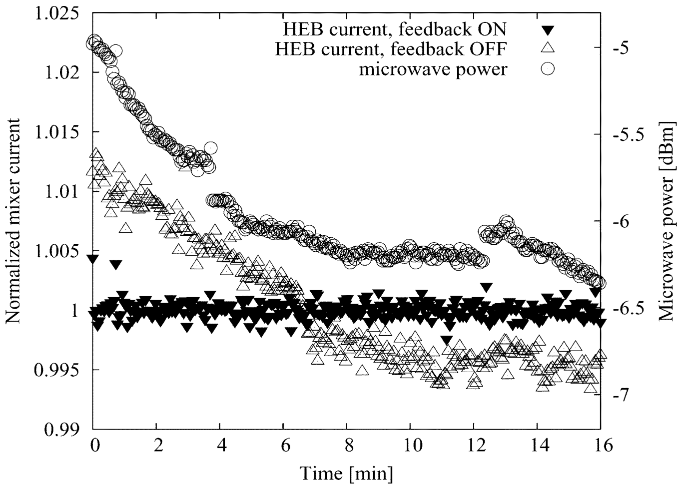

Fig. 4. HEB mixer current versus time with the feedback loop open (open up triangles) and closed (filled down triangles). Also shown is the level of injected microwave power (open circles).

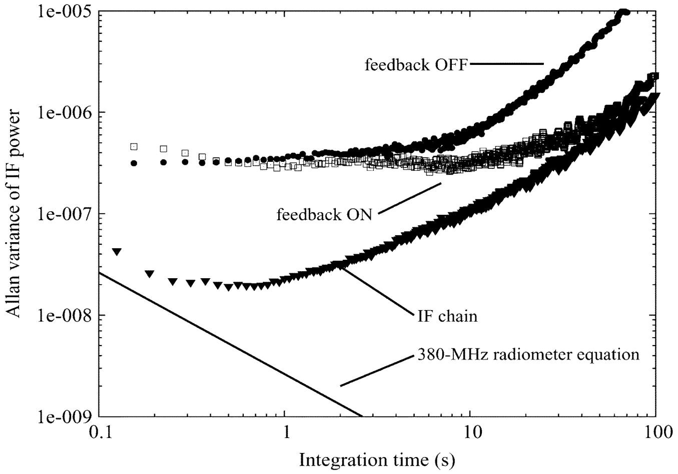

Fig. 5. Allan variance of the HEB receiver with the feedback loop turned OFF and ON. Also show is the Allan variance plot for the IF chain and the 380-MHz radiometer equation.

in the LO power from affecting the mixer impedance) and scanning the output voltage of the power detector. We also note that there is no difference in stability when the mixer is biased at 0 V or at some high bias value into the normal region. In both cases the Allan plots of the IF chain look very similar.

The results of the measurements are presented in the Allan variance plot given in Fig. 5. The Allan variance plots of the receiver at the operating point show a plateau from about 1–10 s, which indicates the presence of $1/f$ noise. This type of noise is absent, however, from the IF chain Allan variance data. Kooi *et al.* [17] have shown that as the frequency of the LO increases above 2.8 THz, the contribution of $1/f$ noise becomes less, from which they conclude that this type of noise is likely to do with certain processes in the hot spot of the mixer. However, separate measurements of the stability of the LO power, by monitoring the current flowing in the second stage of the varactor multiplier, indicate that $1/f$ noise may also come from the LO itself. It is likely that the type of LO has a significant impact on the amount of additional fluctuations induced in the receiver.

As can be seen from Fig. 5, the use of the feedback loop improves the receiver stability by extending the point of the crossover from $1/f$ noise to drift up to about 10 s. This means that in the total power mode, the integration can be performed for about 10 s without deteriorating the receiver signal-to-noise ratio. In the case of the open loop operation, integrating for the same amount of time will result in the degradation of the receiver performance. Comparison of the Allan plots for the IF chain and the receiver at the operating point with the closed feedback loop shows that the IF chain sets the limit to the receiver performance by causing its output to drift.

Allan variance measurements allow us to estimate the temperature resolution of the receiver. Referring to (2), $\Delta T_{\min} = \min(T_{\text{sys}}\sigma_A)$, where T_{sys} is the system temperature, equal to the sum of the receiver noise temperature and the antenna temperature; and σ_A is the measured relative Allan variance (the Allan variance divided by the square of the expectation value). In our case, $T_{\text{sys}} = T_A + T_R \approx 800\ \text{K} + 300\ \text{K} = 1100\ \text{K}$, the minimum values of σ_A are 7×10^{-4} and 5.5×10^{-4}, respectively, for the open and closed loop operation. This yields a temperature resolution of 0.8 K and 0.6 K for the open and closed loop, respectively, and an integration time of 5 s.

For the same system temperature and integration time, the radiometer equation would predict a theoretical minimum temperature resolution of about 0.03 K, which is better by a factor of 20 for closed-loop operation, and close to 30 for the open loop case. This substantial deviation from the radiometer equation is much in line with the finding that the HEB mixer is a relatively poor continuum detector [17]. We were able to confirm in a separate set of experiments that the HEB receiver provides a better resolution when used as a spectroscopic instrument [26].

VII. CONCLUSION

In summary, we have demonstrated that our microwave feedback scheme can eliminate the drift of the output power in the HEB receiver, thereby increasing the Allan time up to 10 s and improving the temperature resolution of the receiver by $\sim$30%. The absence of the $1/f$ noise signature in the Allan plot of the IF chain indicates that this type of noise may either originate in the mixer itself or be entirely caused by the LO.

ACKNOWLEDGMENT

The authors would like to thank S. Paine and R. Wilson for help with C-code development, and also R. Kimberk and A. I. Elantiev for stimulating discussions.

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