Stabilisation of a Terahertz Hot-Electron Bolometer mixer with microwave feedback control

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ABSTRACT

We report on implementation of microwave feedback control loop to stabilise the performance of an HEB mixer receiver. It is shown that the receiver sensitivity increases by a factor of 4 over a 16-minute scan, and the corresponding Allan time increases up to 10 seconds, as opposed to an open loop value of 1 second. Our experiments also demonstrate that the receiver sensitivity is limited by the intermediate frequency chain.

Keywords: hot-electron bolometer mixers, IF chain stability, Allan variance, Allan time.

1. INTRODUCTION

In radio astronomy, signals collected by a radio telescope are usually weak and the corresponding antenna temperature is much lower than the receiver temperature. Therefore, it is necessary to integrate the receiver output over a certain time interval in order to get a reasonable signal-to-noise ratio:

$$x(t,\tau) = \frac{1}{\tau}\int_{t}^{t+\tau} s(t')dt' , \tag{1}$$

where $s(t)$ is the receiver output (e.g. voltage from the power detector) and τ the integration time. However, if several such measurements of $x(t, \tau)$ are made, they in general will give different results, so one calculates the variance of $x(t, \tau)$ in order to determine how $x(t, \tau)$ changes in time:

$$\sigma^2(\tau) = \left\langle \left(x - \langle x \rangle\right)^2 \right\rangle = \left\langle x^2 \right\rangle - \langle x \rangle^2 . \tag{2}$$

The Allan variance is then defined as half the standard variance[1]:

$$\sigma_A^2(\tau) = \frac{1}{2}\sigma^2(\tau). \tag{3}$$

Ideally, if there is only white noise in the system the signal-to-noise ratio will increase as the square root of the integration time[2]. This means that, given a receiver with a certain system noise temperature T_{sys} and noise bandwidth B, one can reduce the uncertainty in the antenna temperature, ΔT, by simply increasing the integration time:

$$\frac{\Delta T}{T_{sys}} = \frac{1}{\sqrt{B\tau}} . \tag{4}$$

In practice, however, one has to deal with at least two more types of noise: 1/f- (flicker) noise and drift noise. It can be shown[3] that if all of the above types of noise are present in the system, the Allan variance will be

$$\sigma_A^2(\tau) = \frac{a}{\tau} + b + c\tau^{\beta} . \qquad (5)$$

The three terms in (5) represent white noise, 1/f-noise and drift noise respectively; the exponent β in the drift noise term lies typically between 1 and 2[4]. Equation (5) reaches its minimum at what is called the Allan time, which marks the crossover from white noise to 1/f-noise and drift and is the maximum integration time for the receiver. Integrating longer than the Allan time will result in the worsening of the signal-to-noise ratio. Nor is it useful to integrate as long as the Allan time since doing so will not improve the signal-to-noise ratio much and will only result in the loss of the efficiency of observation. Plotting the Allan variance vs. integration time is a useful tool enabling one to estimate relative contributions of the three types of noise mentioned above and also determine the optimum integration time.

Currently, hot electron bolometer (HEB) mixers are detectors of choice for most terahertz heterodyne receivers because they offer a very low noise temperature, typically 1K/GHz[5], and require much less local oscillator (LO) power than their Schottky diode predecessors[6]. Unfortunately, most HEB receivers typically have an Allan time of less than 5 seconds[4], which is significantly shorter than that for SIS receivers operating below 1 THz[7] and competing Schottky diode based receivers.

In this paper we propose a microwave feedback control loop to compensate for local oscillator power fluctuations. The use of this feedback loop is shown to reduce the fluctuations of the intermediate frequency (IF) power of the receiver and increase the corresponding Allan time.

2. EXPERIMANTAL SETUP

Fig. 1 shows a schematic of the experimental setup. The HEB mixer element is installed into a half-height waveguide mixer-block mounted onto the cold plate of the liquid helium cryostat. A Gunn oscillator, operating at 90 GHz, followed

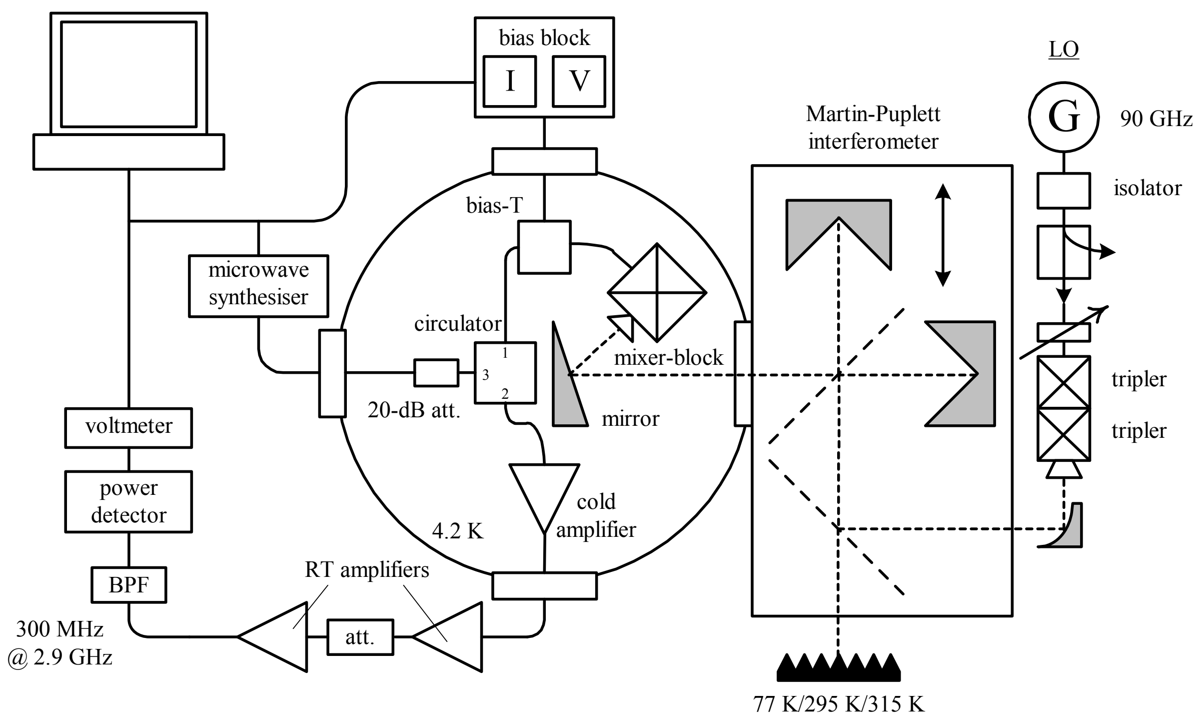

Fig.1: Schematic of the experimental setup.

by two solid state frequency triplers, provides local oscillator (LO) power at a frequency of 810 GHz. The signal and LO are combined in a Martin-Puplett Interferometer, pass through a 0.5-mm Teflon vacuum window and two Zitex G106 infra-red filters mounted onto the 77-K radiation shield and the cold plate respectively, and are finally directed into the corrugated feed horn of the mixer-block by a 30-degree offset parabolic mirror mounted on the cold-plate of the cryostat. A microwave synthesiser (HP83630A) serves as a remotely controllable microwave injection source when the receiver is operating with the feedback loop turned on. The output of this synthesiser is coupled to the HEB mixer via the 3rd port of the cold circulator through a 20-dB attenuator which reduces possible noise coming from outside the cryostat.

Since the frequency of the injected microwave signal is much lower than the LO frequency it will not introduce any spurious mixing tones. On the other hand, it should also be much higher than the mixer cut-off IF[8] so as not to interfere with the mixer IF output. We have selected 17 GHz for the microwave signal as this meets the above criteria and allows coupling the signal to the HEB element quite easily.

The IF output from the mixer passes through the bias-T and circulator to the cryogenic amplifier with a gain of 30 dB in the frequency range 2-4 GHz and then to a room temperature IF chain. The latter consists of two amplifiers with a gain of 26 dB in the frequency range 1-4 GHz. In noise temperature measurements the amplifiers are followed by a 2.4-3.6 GHz band-pass filter and the power meter HP436A. For stability measurements we use a 300-MHz band-pass filter centred at 2.9 GHz, a tunnel diode Herotek power detector loaded by a 120-Ω shunt resistor. The detector voltage is measured by the digital multimeter HP34401A.

3. EXPERIMENTAL RESULTS AND DISCUSSION

We used the standard Y-factor procedure to measure the DSB noise temperature of the receiver vs. bias voltage and current and thus determined the low-noise operating point. It was also possible to estimate the mixer gain at the same point:

$$G_M = \frac{T_{bath} + T_{HEMT}}{P(V_{bias} = 0)} \frac{P_{hot} - P_{cold}}{T_{hot} - T_{cold}}, \tag{6}$$

where T_{bath} = 4.2 K – the He bath temperature, T_{HEMT} ~ 4 K – the noise temperature of the cold amplifier; $P(V_{\mathrm{bias}} = 0)$ is the IF chain output when the HEB mixer is not biased and the LO is turned off; T_{hot} = 295 K and T_{cold} = 77 K are hot and cold load temperatures respectively. Note, however, that (6) gives the mixer gain averaged over the output bandwidth.

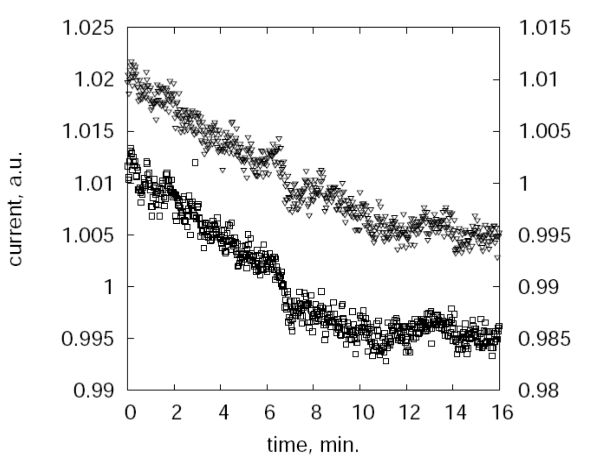

Fig. 2: Mixer current (squares) and IF power (triangles) vs. time with the feedback control turned off.

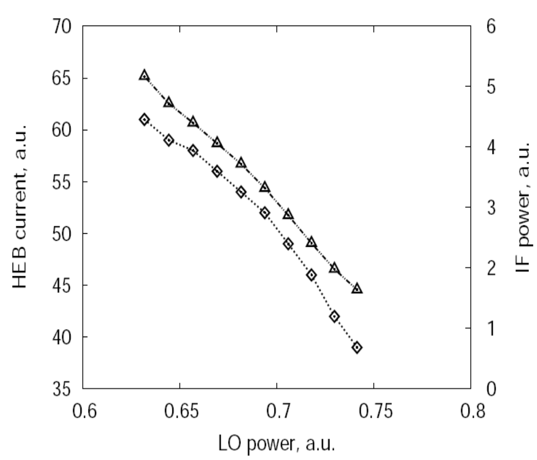

Fig. 3: Mixer current (diamonds) and IF power (triangles) vs. LO power

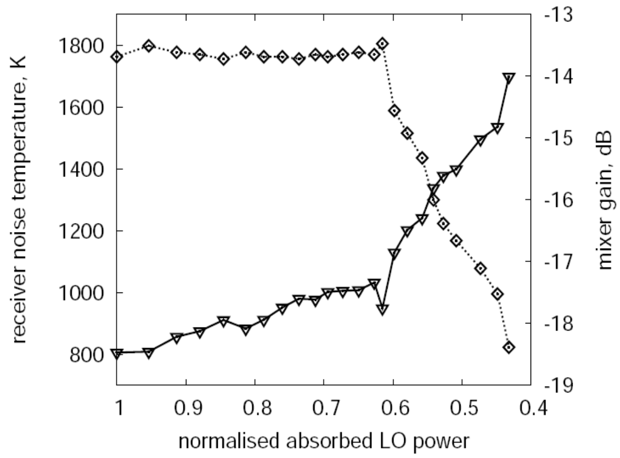

Fig. 4: Receiver noise temperature (triangles) and mixer gain (diamonds) vs. LO power normalised to the LO power level at the low-noise operating point.

In order to determine the stability of our receiver we fixed the bias voltage of the HEB mixer, set its current by adjusting the level of the LO power and then measured the operating current and IF output vs. time. As can be seen from fig. 2, both the mixer current and IF power fluctuate quite strongly and demonstrate very strong correlation as well. To check the latter we explored the dependence of the current and power on the level of LO drive near the low noise operating point. Fig. 3 shows that the dependence is almost linear, which suggests that the IF power is a linear function of the mixer current near the operating point. The last statement should not, of course, be taken at its face value since it is the LO drive, not the current that is the determining factor. However, if somehow it were possible to keep the operating point of the receiver fixed it might be possible to stabilise the IF power as well. This is the main idea behind our microwave feedback control loop.

Before implementing the microwave feedback scheme we needed to know the possible effect that microwave radiation might have on the performance of the HEB receiver in terms of its noise temperature and gain.

Once the low noise operating point was found, we reduced the LO drive level to increase the mixer current. The current was then restored to its original optimal value by injecting the appropriate amount of microwave radiation at 17 GHz. We then made a series of similar measurements, compensating for the decreasing LO power by increasing the

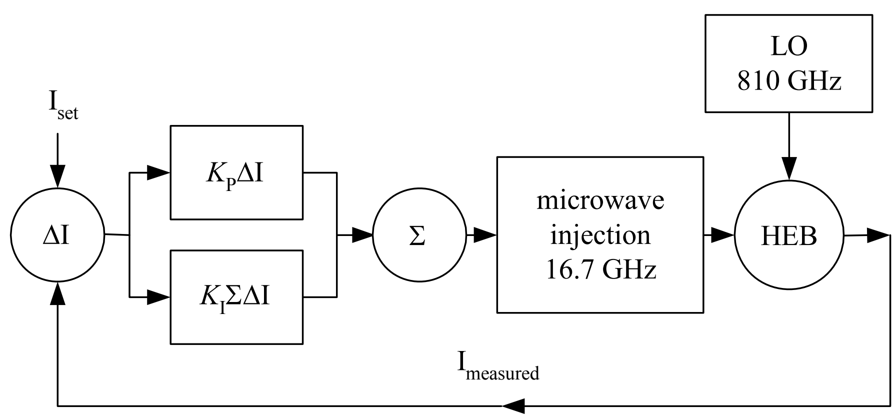

Fig. 5: Schematic of the feedback control loop

microwave injection at each step. In this way we derived the noise temperature and conversion gain as a function of terahertz LO drive normalised to the optimal LO drive level. The mixer bias voltage remained fixed in all measurements.

Fig. 4 summarises the results of our measurements. One can conclude that so long as the relative change of the LO power level is less than 10 % there is no significant degradation of the HEB receiver performance – the noise temperature and gain are practically unaffected by microwave radiation.

Our feedback loop (fig. 5) comprises proportional and integral terms: the mixer current is measured and compared to the preset value and the microwave power is then readjusted according to the formula:

$$P_{\mu wave}(t) = P_0 - K_P \cdot \Delta I(t - t_{sampl}) - K_I \cdot \sum_{t'=t_{sampl}}^{t'=t} \Delta I(t' - t_{sampl}), \tag{6}$$

$$\Delta I(t - t_{sampl}) = I_{meas}(t - t_{sampl}) - I_{set}, \tag{7}$$

where P_0 is the initial level of the microwave power at the synthesiser output, typically -10 dBm; K_P is the proportional term coefficient, typically -0.1-0 dB/μA; K_I is the integral term coefficient, typically -0.1 dB/μA; $I_{meas}(t)$ is the mixer current, I_{set} is the preset value of the mixer current, $t_{sampl} \approx 30$ ms, the sampling interval.

Fig. 6 shows the mixer current and IF output vs. time with the feedback control loop turned on. Comparing fig. 2 (no feedback) and fig. 6, we see a marked improvement of both current and IF power stability. The calculated standard deviation of the IF power over a period of 16 minutes is 4 times as low as that for the open loop system. Fig. 7 presents the results of the Allan variance measurements. As is seen from the figure, in the case of the open loop system, the Allan time is about 1 second. Turning the feedback on suppresses the drift of the IF power and increases the Allan time up to 10 seconds. However, it can also be seen that the contribution from the IF chain becomes significant for integration times greater than a few seconds. This shows that the stability of our IF chain needs further improvement to allow full assessment of the potential of the microwave feedback loop.

4. CONCLUSIONS

We have developed and tested a microwave feedback control loop for stabilising the HEB receiver output. Our measurements show a four-fold improvement in the receiver stability when a feedback loop is operating. Additional experiments are underway to eliminate the contribution of the IF chain to the receiver instability. It has also been shown that the use of the microwave feedback loop does not cause any significant degradation of the HEB receiver performance.

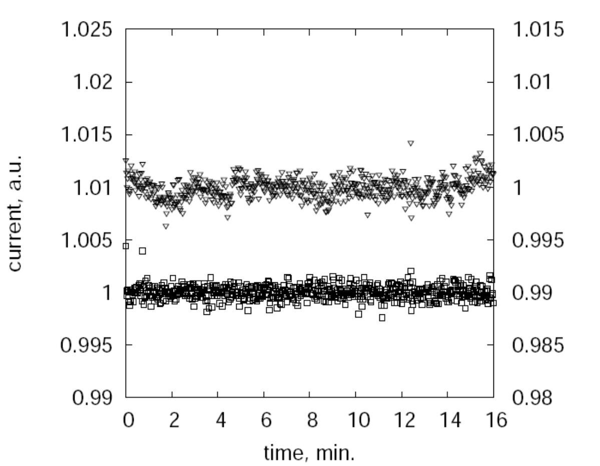

Fig. 6: Mixer current (squares) and IF power (triangles) vs. time with the feedback control turned on.

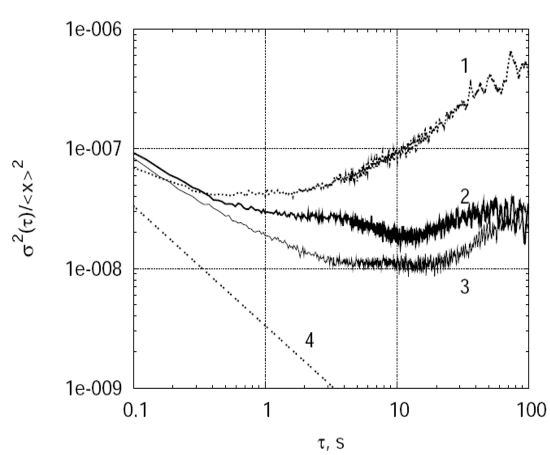

Fig. 7: Normalised system Allan variance: 1 – feedback turned off; 2 – feedback turned on; 3 – If chain; 4 – radiometer equation.

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