Stability Measurements of a NbN HEB Receiver at THz Frequencies

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Abstract

To improve the signal to noise ratio, the operation of a receiver for radio astronomy applications requires an integration of the received signal over a certain time. When the integration time is too short, the effective observation time suffers from unavoidable black-out periods. Simultaneously an increase of the integration time is limited by the system stability, which consists of the stability of the mixer itself, the local oscillator (LO), the bias network and the read-out electronics. Using three LO-sources: a far infrared laser (FIR), a backward wave oscillator (BWO) and a multiplication chain, we have measured noise and gain stability of NbN hot electron bolometer (HEB) mixers of different sizes. As a stability measure we used the Allan variance time. We found that small HEB mixers are more unstable due to stronger noise-to-LO power dependence. For each HEB mixer size, we present data over stability and receiver noise temperature and discuss the trade off between system stability and noise.

Introduction

Due to the atmosphere's low transmission of radiation at terahertz frequencies, the receivers used to observe this radiation are usually placed on high and dry places or sent out in space. To use the observation instruments on these very remote places is expensive. It is therefore important that time is optimized to suit the wanted observation method (e.g. beam-, frequency-, position switching, etc), as discussed by Schieder and Kramer [1].

Radio astronomical receivers generally detect very weak signals deeply embedded in noise. To extract the signal of interest, synchronous detection is often used, i.e. the receiver is switched between on and off signal. However, since it takes a certain time to make this switch high chopping frequency will interrupt the integration time with many black-out periods. On the other hand low chopping frequency will give long observation time. However, the integration time is limited by the stability of the receiver.

If the noise is uncorrelated (white), it will, through integration, reduce independently of the chopping rate according to the radiometer equation:

$$\sigma = \frac{\langle x(t) \rangle}{\sqrt{B\tau}}$$

where σ is the standard deviation of the signal fluctuations, $\langle x(t) \rangle$ is the signal mean, B is the bandwidth and τ is the integration time. In addition to white noise there is also drift and 1/f-noise in a real astronomical heterodyne receiver. Longer integration time does not necessarily give better signal-to-noise ratio since the noise is not uncorrelated. A method to determine the optimum integration time for a system is to measure and plot the Allan variance.

During the last ten years the phonon-cooled hot electron bolometer (HEB) has shown promising low noise properties for spectroscopic detection in the terahertz frequency regime [2]. Large efforts have been made to minimize noise, maximize the IF bandwidth and to achieve a theoretical understanding of the HEB. However, before the HEB detector can be fully integrated into a receiver, the stability of the device must be thoroughly investigated. In this paper we investigate stability of HEB receiver with regards to the bolometer size, type of local oscillator and IF chain.

The Allan Variance

To obtain the Allan plot used to determine the Allan time, we record the output power of a HEB receiver chain. We call the data points p_n n=1,...N, where N is 10^3-10^4. These values are grouped in M groups of K data points and averaged within the groups

$$X_i(K) = \frac{1}{K}\sum_{n=1}^{K} p_{(iK+n)} \qquad i = 0,...M \qquad M = N/K - 1$$

The Allan variance is then calculated using

$$\sigma_A^2(K) = \frac{1}{2M}\sum_{i=1}^{M}(X_{i+1}(K) - X_i(K))^2$$

The variance is plotted as a function of the integration time $\tau = Kt$, where t is the time between the data points [3].

There are three main contributions to be aware of in the Allan plot [4]. The first is the white noise. It follows the radiometer equation and has a slope equal to -1. It is the left part in the Allan plot, see fig. 1. The second contribution is the 1/f-noise which has a slope equal to zero and will therefore not be reduced by longer integration. The last contribution is low frequency drift noise. This has slope ≥1 and is usually found for longer integration time in the Allan plot. Thus longer integration time will only give less efficient observations and not lower noise level if drift noise is present. These three contributions can be summarized as

$$\sigma_A^2(T) = \frac{a}{T} + b + cT^{\alpha}$$

Where *a*, *b* and *c* are appropriate constants. The Allan time (T_A) is defined as the integration time where the Allan plot deviates from the radiometer equation. Integration longer than the Allan time is not efficient and might reduce signal to noise ratio.

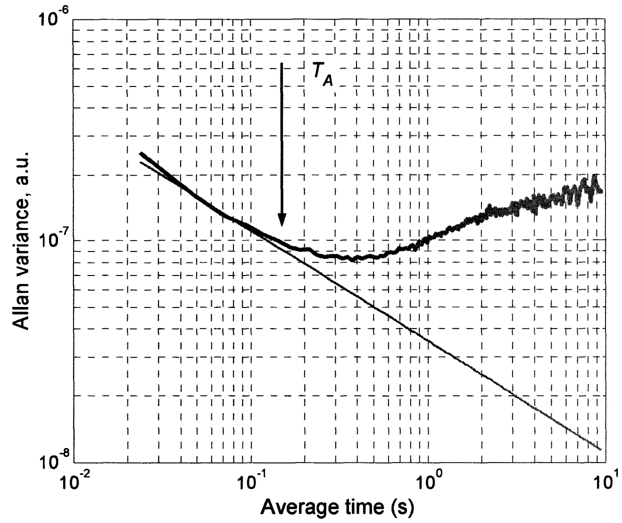

Figure 1 A Allan variance plot. The straight line shows the radiometer equation. The leftmost slope shows how white noise is integrated down, the middle part is the 1/f-noise and the right slope comes from slow drift phenomena.

Measurements

HEB mixers with bolometer size of 4x0.4 μm^2, 2x0.2 μm^2 and 1x0.15 μm^2 have been used. They are made of 3.5 nm thick NbN films. The films are processed with e-beam lithography as described in [5].

Three types of local oscillators were used: a FIR gas laser, a solid state source or a Backwards Wave Oscillator (BWO). The former is a ring gas laser pumped with a CO_2 laser. CH_2F_2 gas provided 1.63 THz and 0.69 THz lines. The solid state source is a chain consisting of three power amplifiers and four diode doublers. The chain is pumped with a 95 GHz Gunn diode oscillator to obtain an output signal of 5-10 μW at 1.5 THz. As an alternative to the Gunn oscillator, a 15.8 GHz synthesizer with x6 multiplier was also used with the output power of 5 mW. The solid state source is a Band 6 Low LO prototype for the Herschel Space Observatory. The BWO radiates at approximately 600 GHz.

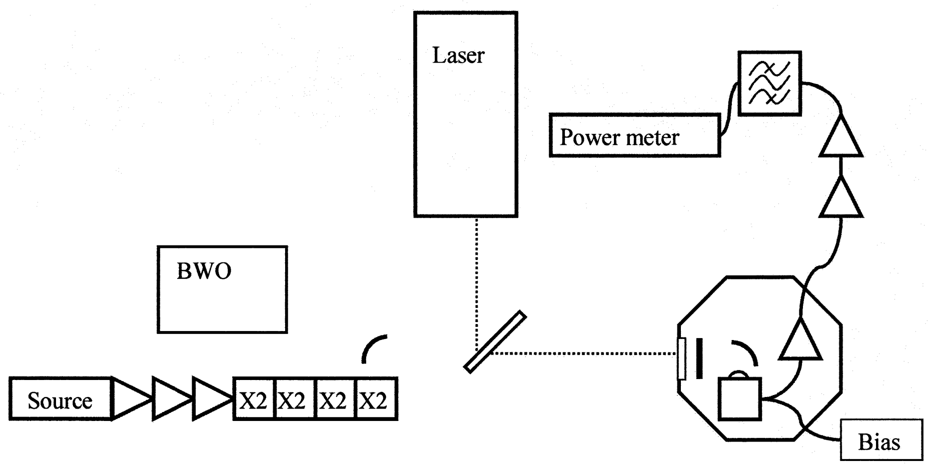

Figure 2 The setup: LO source, beam splitter (only used with the laser), cryostat with the mixer unit and LNA, room temperature IF chain with two Miteq amplifiers, a 30 MHz YIG filter and the power meter.

To measure the noise temperature of the receiver, the Y factor method is used. The cold load is an absorber in a bath of liquid nitrogen placed approximately 50 cm from the mixer. The radiation is transmitted via a mirror and chopped with the hot load, i.e. a chopper covered with Eccosorb at 295 K. During measurements with the FIR laser the LO signal is coupled into the mixer via a beam splitter made of thin polyethylene. An elliptical mirror and a parabolic mirror were used to match the beams of the LO and the mixer. Verification of the noise temperature of the HEB receiver was done with the FIR laser, as well as with the BWO. The noise temperature results are uncorrected.

The bolometer is integrated with a double slot antenna optimized for 1.6 THz. The HEB chip is glued on a 5 mm elliptical lens mounted in a HIFI band 6 prototype mixer unit. It is connected to a 2-4 GHz InP (Chalmers) LNA without an isolator in between. The cryostat is cooled with LHe.

The signal from the mixer is further amplified at room temperature with two 0.1-12 GHz Miteq amplifiers and filtered with a YIG-filter. The bandwidth of the filter is 30 MHz and it is tuned to 2 GHz. A HP power meter E4419B with an E4412A power head is used as IF detector. The detected signal is sampled with 40 Hz with the help of GPIB and Labview.

Stability Budget

The resulting Allan time that we measure represent the overall receiver stability. It is important to try to identify the part of the receiver that limits the stability. In general, one should pay attention to disturbances like thermal drifts of the amplifiers and microwave detector, instruments warming up etc. Some of the details in the setup are analyzed further below.

When it comes to the stability of the HEB mixer itself, the mixer bias and LO power plays an important role. The IF output power as a function of current for changing LO power level is plotted in fig. 4a. They are obtained by following a vertical cross-section of the iv-curves (fig. 3). If the mixer is in the operation point it will react on all small changes in LO power amplitude, due to that the curves which are close to optimum operation point (0.7 mV and 1 mV) are steeper than the curves taken at higher bias (5 mV). The stability of the bias point also affects the output noise stability. How big this effect will be is determined by the steepness of the output power vs. bias voltage curve (fig. 4b).

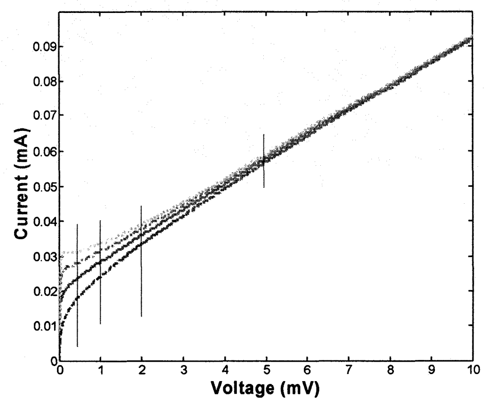

Figure 3 A set of iv-curves, increasing LO power from dotted green curve to dashed blue.

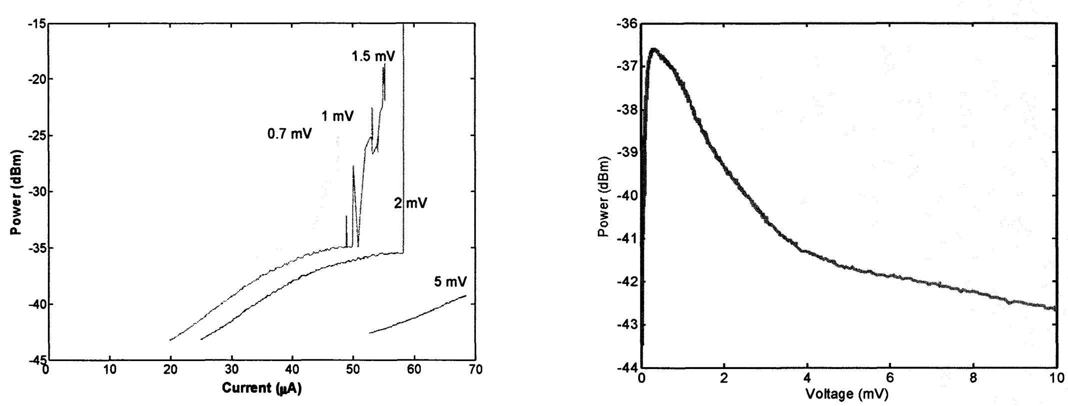

Figure 4 (a): Output IF power as a function of the HEB current for changing LO pumping levels. The curves are obtained along the vertical black lines (constant bias voltage) in fig.3. (b): Output IF power as a function of bias voltage.

Another device in the setup which will affect the stability result is the LNA. The output noise from the mixer is 5-10 dB above the IF-chain noise, therefore gain fluctuations from the amplifier will immediately be detected (fig. 5). The noise from the IF-chain can be investigated with the mixer at a high bias point when the HEB basically acts as a resistor. The influence from the LO and mixer bias is according to fig. 4 minimized. The problem is that the amplifier characteristics changes when the input impedance is changed. A LNA which is unconditionally stable with a resistor on the input can be unstable and oscillate when another impedance is present at the input.

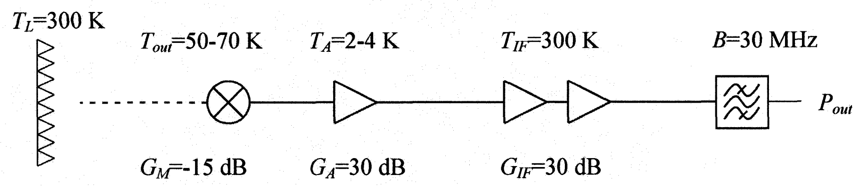

Figure 5 Noise budget

The total output power is

$$P_{out} = k_B B(2 \cdot T_L \cdot G_M \cdot G_A \cdot G_{IF} + T_{out} \cdot G_A \cdot G_{IF} + T_A \cdot G_{IF} + T_{IF})$$

Another factor which influences the amplifier is the bias source and at which bias point it is used. How sensitive the amplifier is depends on the design, type of transistor etc. Further investigations of the amplifier alone need to be done.

As a reference case in the Allan measurements we used the mixer biased to the resistive state. It is also possible to use the superconducting state. The difference is that the mixer does not produce any noise in the superconducting state and it will reflect the signal that comes from the input of the LNA. The risk of standing waves and oscillations in the amplifier is bigger.

Variations in LO power can come from both mechanical and electrical instabilities in the source. The former can for instance come from vacuum pumps or water cooling systems. In the FIR laser the resonating length is determined by grids moved by motors and pietzo crystals. Any instability in the position of the grid will be translated to fluctuations in the LO power. In the case of a solid state multiplier LO electrical oscillations can come from the biasing of the multiplier elements (i.e. diods), the power amplifiers or from the Gunn diode.

The optical path goes through room temperature air before it enters the cryostat. Possible fluctuations and effects from standing waves in the air are investigated by J.W. Kooi [6].

Results

Below the results follow as Allan plots categorized after which LO source that is used to pump the mixer. Noise temperatures are also indicated. The results are summarized in a table at the end.

Measurements with the FIR laser at 1.63 THz.

The time where the measured curve deviates from the radiometer equation line (T_A) is 2.5 s for the 4x0.4 μm^2 sized device. Noise temperature at optimum bias point (curve 2 in fig. 6) is 750 K. The mixer is in superconducting state as a reference case. The blue curve (1) is obtained with the mixer at higher bias voltage than optimum. For the 2x0.1 μm^2 device is the light blue curve (4) in fig. 7 measured in the optimum operation point (1 mV, 35 μA). The noise temperature is then 1250 K and the Allan time 0.2 s. For more (green curve (5), 30 μA) respectively less (pink curve (2), 45 μA) pumped device changes the stability, the Allan time for curve 2 and 5 is 0.1 s and 0.5 s, respectively. However, the noise temperature is 1500 K for both cases. The third device that we measured with the laser at 1.63 THz has the size 1x0.15 μm^2. The resulting Allan time is plotted in fig. 8. The LO power level is constant; the measurements are done at different points along one iv-curve. The stability at optimum operation point (between the purple (1) and the pink curve (2)) is 0.1 s. The lowest noise temperature measured for this device is 1550 K.

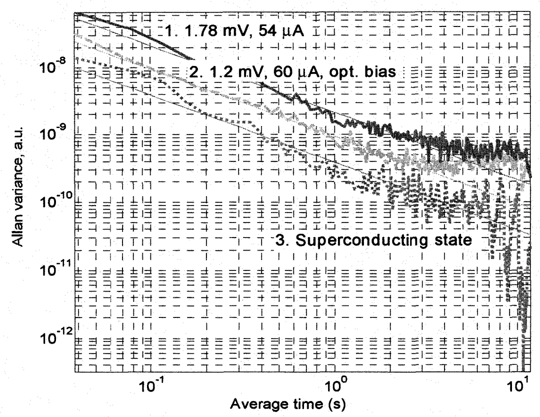

Figure 6 4x0.4 μm², FIR laser at 1.63 THz. Green curve (2) is optimum.

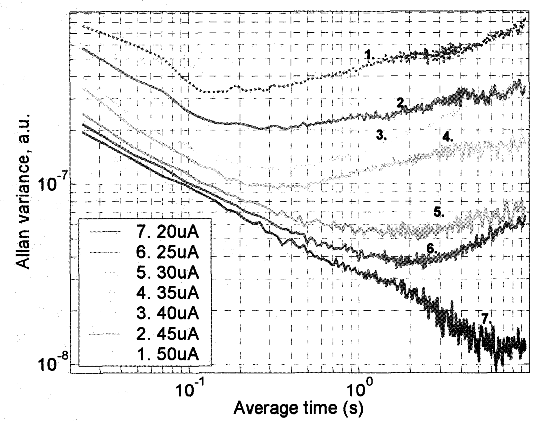

Figure 7 2x0.1 μm² device, FIR laser at 1.63 THz. Bias voltage is 1 mV, LO power level varied. Llight blue (4) curve is measured in optimum bias point..

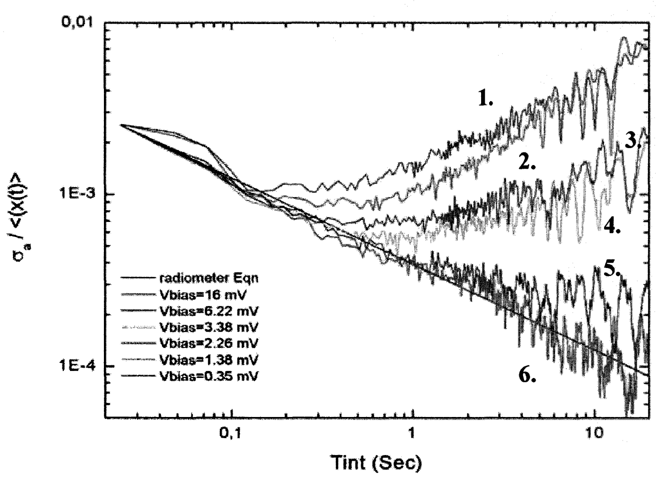

Figure 8 1x0.15 μm² device measured with FIR laser at 1.63 THz.

Measurements with the solid state LO at 1.5 THz.

It was only enough power to pump a small device (1x0.15 μm²) with the solid state LO. It is the same device as was measured with the laser in fig. 8. The curves in fig. 9 are obtained in the same way as in fig. 8, with constant LO power level and different bias voltages. The Allan time for the optimum point (pink curve (2) with bias 0.6 mV) is 0.2 s. The noise temperature is 1550 K. The effect of varying the pump level with the device in optimum voltage bias point was also investigated. The results for three pump levels are shown in fig. 10. The red curve (4) is the reference case with the mixer in resistive state. The best Allan time is the same as in fig. 9, 0.2 s for the optimum curve (green curve (2)).

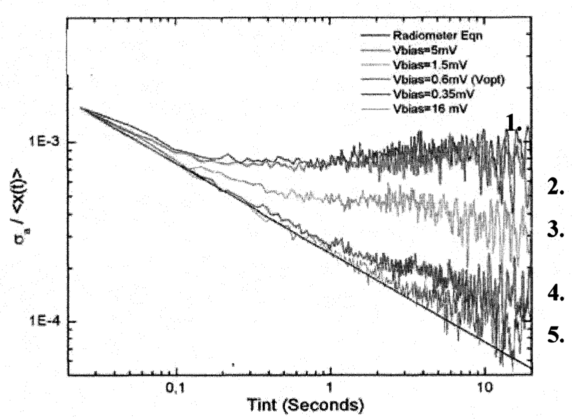

Figure 9 1x0.15 µm device measured with the solid state LO at optimum power level with varied bias voltage.

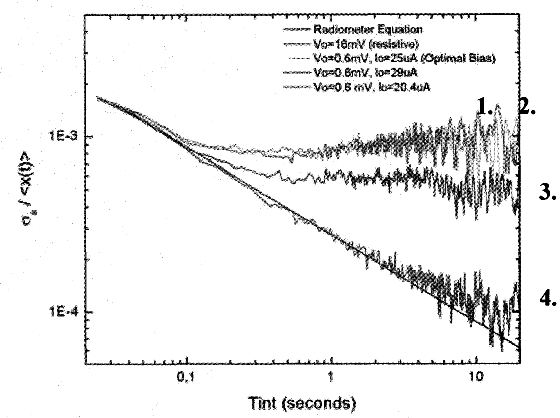

Figure 10 A 1x0.15 µm device measured with solid state LO. The LO pump level is varied.

Measurements with the BWO at 0.6 THz.

The middle sized (2x0.1 μm^2) device was also measured with a BWO at 0.6 THz. The resulting Allan time is 0.4 s (fig. 11). The antenna of this device is designed for 1.6 THz. However, a Y-factor of 0.2-0.3 dB was measured at 0.6 THz. During the measurements with the BWO we discovered that the bias of the LNA influenced the Allan time. This was not the case during the first measurements with the laser and the solid state LO. The measurements are done in the optimum bias point of the device for three settings of the LNA bias.

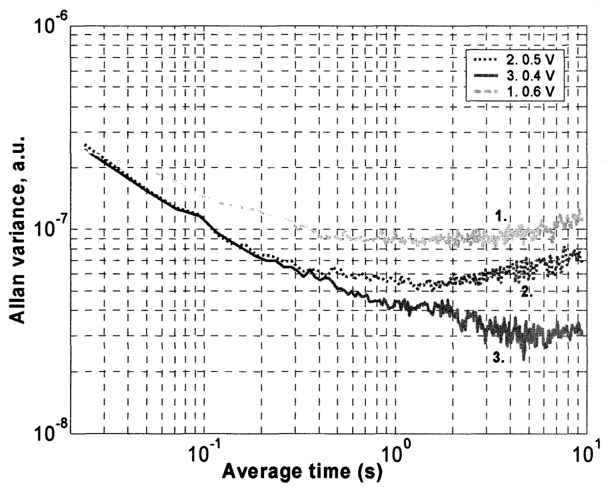

Figure 11 2x0.1µm2 device. BWO at 600 GHz, varying LNA bias

Measurements with the FIR laser at 0.69 THz.

To verify whether the improved result with the BWO was due to the LO itself or an effect of the lower frequency, we repeated the measurement with the laser tuned to 0.69 THz. The Allan time with the laser is 0.5 s with the best setting of the LNA (fig. 12).

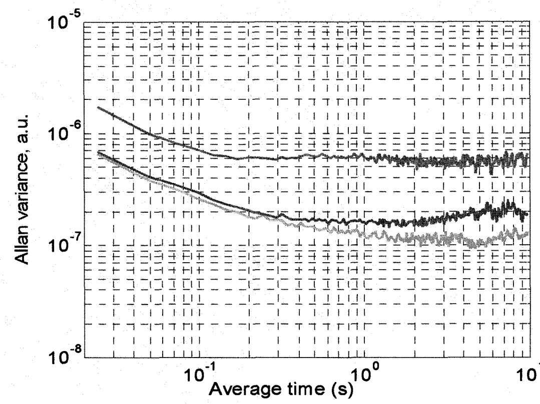

Figure 12 The bias to the LNA is varied. Measured with laser at 0.69 THz, device size is 2x0.1 μm^2.

Table 1 Allan time results summarized

Device size	FIR 1.63 THz	Solid state 1.5 THz	BWO 0.6 THz	FIR 0.69 THz	T_r
1x0.15 μm^2	0.1 s	0.2 s			1550 K
2x0.1 μm^2	0.2 s		0.5 s	0.4 s	1250 K
4x0.4 μm^2	2.5 s				750 K

Conclusions

To measure stability of HEBs has shown to be a challenging task. It is difficult to draw clear conclusions from the results but a few tendencies can be commented. The size of the HEB plays a role; a larger device is more stable. A larger device also has better noise properties, but the drawback is that it needs more LO power to be pumped to the optimum point. A higher bias voltage and more LO power also gives more stability, as expected. When it comes to the different types of LO source it looks like the drift behaviour can be stronger with the laser. Compare for instance fig. 8 and 9. Otherwise it looks like the 1/f-part of the noise is limiting the stability of the overall receiver. The BWO gives a longer Allan time than both the laser and the solid state LO, this effect comes partly from the fact that the LO frequency is lower. One area that we will investigate further is the role of the amplifier.

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