Linearity Measurements of the 640 GHz SIS Mixer for JEM/SMILES

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Abstract— **The nonlinearity of SIS mixers is a critical issue for several new instruments which aim for high accuracy. One of them is the submillimeter wave limb emission sounder JEM/SMILES which will observe the spectral transition lines of various stratospheric trace gases. In this paper we present a perturbation technique which was used to determine the nonlinearity of its 640 SIS mixer. The measurements showed that the incremental gain compression of the mixer is about 0.7% when looking at 300 K black-body radiation.**

I. INTRODUCTION

The nonlinearity of SIS mixers is a critical issue for several upcoming missions which aim for high accuracy. The calibration plan for the HIFI instrument of the Herschel Space Observatory [1] mentions that up to 6% gain compression could be expected from a 300 K thermal source, depending on the bandwidth of the mixer. For a 230 GHz SIS mixer of the ALMA project a nonlinearity of 1% has been determined [2].

The JEM/SMILES instrument [3] is a submillimeter wave limb sounder for atmospheric research on board of the International Space Station. It will measure the spectral emission lines of the stratospheric trace gases O_3, HCl, ClO, BrO and others in two frequency bands around 625 and 650 GHz. Besides an unprecedented sensitivity for the weak emission lines SMILES also has the goal to reach an absolute measurement accuracy of 1%. A nonlinearity of its SIS mixers would lead to a systematic calibration error of the radiometric measurements. In this paper we propose a perturbation method which can be used to measure the nonlinearity of SIS mixers or other receiver components. We have used this method to test the engineering model of the JEM/SMILES mixer.

The SIS mixer of our experiments was fabricated in Nb/Al-AlOx/Nb technology. It has a parallel connecte twin-junctions (PCTJ) design [4] optimized for 640 GHz. Typical values of the SIS junctions are an area of about 1.2×1.2 mm^2, a current density of 7.5 kA/cm^2 and a normal resistance of 20 Ω. The mixer has a double-sideband noise temperature of typically 200 K over an IF bandwidth of 11–13 GHz.

II. EXPERIMENTAL SETUP

The authors A. R. Kerr et al. have described theory [5] and measurements [2] of SIS mixer saturation. For their experiments with a 230 GHz SIS mixer they injected a small CW signal via a waveguide coupler and observed the suppression of its IF amplitude when the thermal noise input to the mixer was chopped between a hot and a cold black-body radiation source. They found an incremental gain compression of 1% by the ambient temperature load. They also identified additional systematic measurement artifacts of 0.5% from the nonlinearity in their IF chain and of 0.5% caused by standing waves between the mixer and the surface of the liquid nitrogen of the cold load.

We tried similar measurements with the JEM/SMILES mixer. This mixer, however, is not equipped with a waveguide coupler because of the much higher frequency of 640 GHz, and the CW test signal had to be injected quasi-optically via a dielectric beam splitter. The SIS mixer and the low-noise IF amplifiers were cooled in our test cryostat by a closed cycle Gifford-McMahon refrigerator which caused significant mechanical vibrations and IF power fluctuations with a 1 Hz periodicity. The stability of this setup was not good enough to detect nonlinearities at the 0.5% level. For that reason we used an alternative ”perturbation method” to determine the gain compression.

In our test setup the field of view of the mixer is terminated through a quasi-optical network either on a cold or a hot black-body radiator. These targets consist of THz absorbers immersed in liquid Nitrogen or at 300 K ambient temperature and they define the thermal noise backgrounds T_C and T_H, respectively. A dielectric beam splitter with a small coupling ration is used to inject a significantly smaller modulated noise

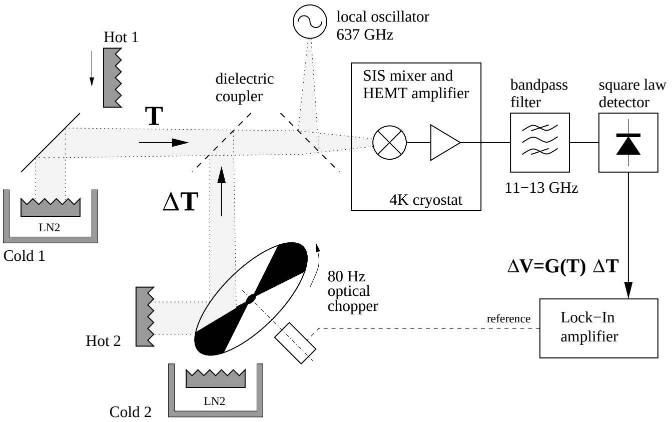

Fig. 1. Schematic measurement setup for the linearity tests.

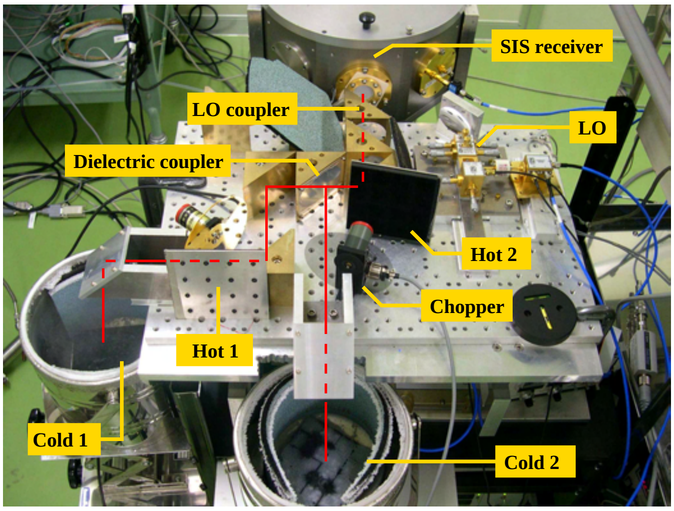

Fig. 2. Optical layout with two hot and two cold loads, optical chopper and dielectric couplers. Additional focusing mirrors are not shown in the schematic in Fig. 1.

offset ΔT which is generated with an optical chopper and an additional pair of hot and cold black-bodies. A second beam splitter is used to inject the signal of the phase-locked 637 GHz local oscillator. The IF signal is amplified by two cryogenic HEMT amplifiers, which are also included in our linearity tests. A 2 GHz wide bandpass filter centered at 12 GHz selects the same IF band that will be used for SMILES. The total power of the IF signal is measured with a fast square-law diode detector which results in an output voltage $V(T + \Delta T)$. The amplitude of the modulated signal ΔV is monitored with a Lock-In amplifier which is phase synchronized with the optical chopper. The schematic overview of the test setup and its quasi-optical layout are given in figures 1 and 2, respectively.

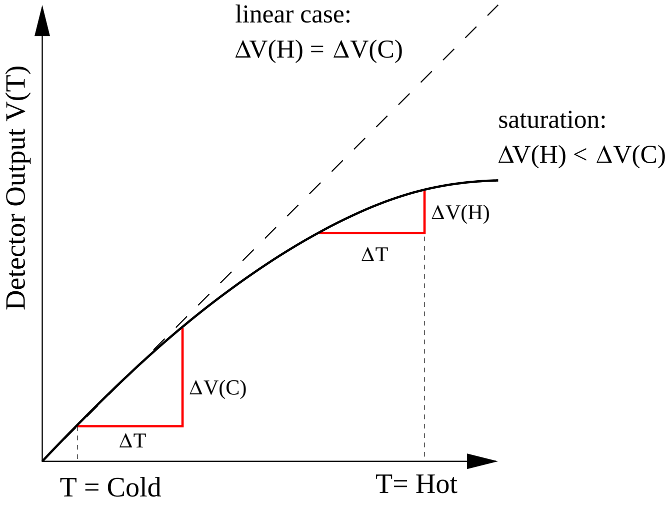

Fig. 3. Measurement principle of the linearity tests. A modulated noise offset ΔT is added to different thermal backgrounds T. The resulting modulated output voltage ΔV of the IF detector remains constant for a linear system, but gets slightly suppressed with increasing T in the case of nonlinearities.

Figure 3 shows the principal idea behind this perturbation method. For a linear system, ΔV is independent from the noise background T, and the Lock-In response will remain constant when T is switched from the cold to the hot load. Any saturation effects of the receiver or the detector, however, will decrease ΔV at the hot background: $\Delta V(T_\mathrm{H}) < \Delta V(T_\mathrm{C})$. Similar to the measurements with CW test signal this determines the incremental, and not the large signal gain compression of the system for a certain input level. As long as the nonlinearities are small, the latter will be approximately half of the incremental compression [2].

The advantages of our method are that the values of T and ΔT must not be known precisely, and that no waveguide coupler and no additional CW submillimeter wave source are required. It is also less sensitive to standing waves which can cause problems with a CW tests signal. The main drawback, however, is that the sensitivity of our measurements is limited by the gain fluctuations of the system. In our case, with the optical chopper running at about 80/ Hz, the integration time of the Lock-In amplifier had to be in the order of 3s to achieve a sufficient signal-to-noise ratio. As a result the minimum switching period for the background T was about 30 s, and the gain of the complete setup needs to be stable over these timescales. Otherwise any gain fluctuation leads to a similar relative change of ΔV. It turned out that the stability of our test setup was always worse than 0.1%, mostly because of the 1 Hz cycle of the mechanical refrigerator, the frequency stability of the chopper and variations of the room temperature. Figure 4 gives an example for these fluctuations. It shows the normalized Lock-In output voltage of a measurement were T remained on the hot load for 120 s.

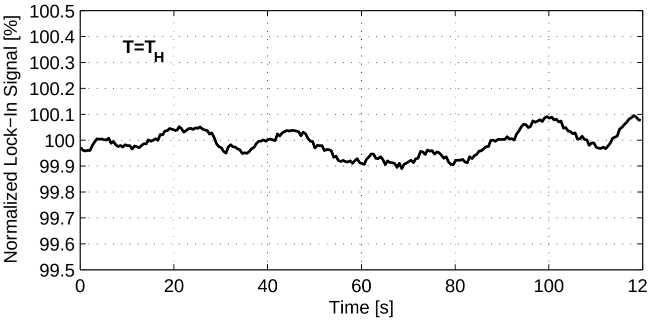

Fig. 4. Example of the instability of the normalized Lock-In output voltage. For this measurement, the noise background remained fixed on the hot load T_H and the time constant of the Lock-In amplifier was set to 3 s.

III. MEASUREMENT RESULTS

Figure 5 shows three independent measurements during which the hot load was replaced manually by the cold load for about 30 s. For each of the measurement series the Lock-In output was normalized with the values where T was on the cold load. With the thermal background of the hot load the signal is suppressed by about 0.5%. The true incremental gain compression is slightly larger because of the finite coupling

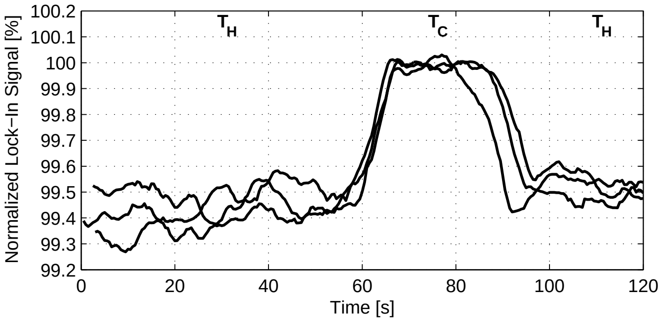

Fig. 5. Linearity measurements where the noise background was switched from the hot load T_H to the cold load T_C for a period of about 30 s and then back. The Lock-In signal has been normalized with the T_C values. The ∼0.5% suppression during the T_H observation results from the SIS receiver saturation by the 300 K background.

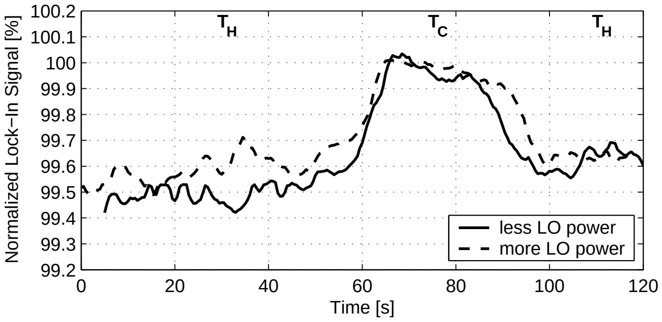

Fig. 6. Linearity measurements where the LO power had been increased or decreased from its optimum level. In this case saturation is slightly lower than in Fig. 5.

ratio of the beam splitter, and also because a small nonlinearity will be already present at the cold load. When the 20% coupling ratio of the beam splitter is taken into account we can estimate that the nonlinearity caused by the 300 K background is about 0.7%.

To study how the nonlinearities are affected by the bias conditions of the SIS mixer the measurements were repeated with different settings of the local oscillator power. For the nominal operation conditions, which maximize the IF power and the noise performance, the LO power is adjusted until the SIS bias current is 45 μA at a constant bias voltage of 1.9 mV. Figure 6 shows measurements with two different LO power levels which led to a ±15 μA increase or decrease of the bias current. In both cases the observed nonlinearity is slightly lower than for the optimum bias conditions.

Care has to be taken that the measurements are not affected by nonlinearities of the IF chain or of the detector. This was done by adding enough fixed attenuators to keep them well below their saturation level. We have confirmed with a similar measurement technique that the effect of the detector nonlinearity is less than 0.1%. For these tests the small modulated offset was injected in the IF chain and the noise background was varied over a wide range using a step attenuator. Figures 7 and 8 show this test setup and the measurement results of two different detectors, respectively.

Another possible measurement artifact are reflections at the calibration loads. Both loads were made of TK-RAM absorbers [6] which have a reflectivity in the order of -50 dB, but from the cold loads reflections of up to -21 dB can be expected from the surface of the liquid nitrogen. In [2], the standing waves between the SIS receiver and the liquid nitrogen caused a periodic modulation of about 0.5% depending on the changing nitrogen level in the load. In our case ΔT consists of broadband noise, and similar standing waves from the coherent reflections will lead to a periodic baseline ripple with a period of less than 150 MHz, corresponding to the distance between the SIS receiver and the liquid nitrogen surface. Averaged over the whole 2 GHz bandwidth of our measurement, this will only have a marginal effect on the linearity tests.

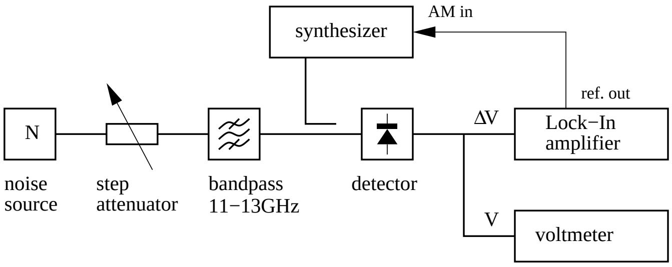

Fig. 7. Measurement setup to determine the detector nonlinearity.

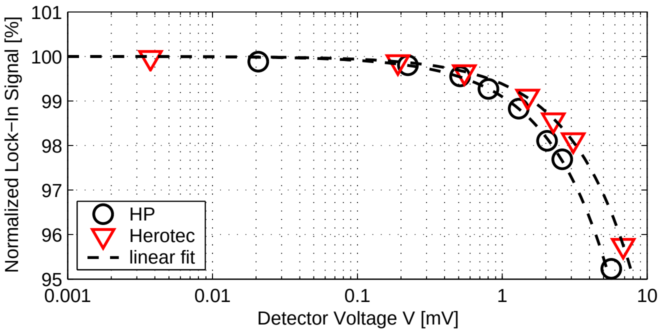

Fig. 8. Test results for the nonlinearity of two different diode detectors. The SIS linearity tests were done at a detector voltage below $V(T_H) < 0.2$ mV where its linearity is better than 0.1%.

IV. DISCUSSION

The theoretical investigation of SIS mixer saturation described in [5] allows to estimate the incremental gain compression as a function of $S_{\text{in}}^2 = (e/Nhf)^2 \, G_0 \, P_{\text{sig}} R_{\text{L}}$, where N is the number of junctions in series, f the local oscillator frequency, G_0 the small signal gain of the mixer, P_{sig} the signal input noise power, and R_{L} the IF load impedance seen by the SIS mixer.

The input noise power from the hot load is expressed as $P_{\mathrm{sig}} = kT_{\mathrm{H}}B$, where B is the input noise bandwidth. Since the SIS mixer was designed to have the relative bandwidth of 12.5%, we may estimate $B = 80$ GHz. This is almost consistent with a measurement result from Fourier transform spectroscopy [7]. Based on the other measurements, we also estimate an SIS mixer gain of -7 dB on average over the band. Finally the IF load impedance is assumed to be 50 Ω over the extended frequency range 0 Hz to B. Thus we obtain $S_{\mathrm{in}}^2 = 4.4 \cdot 10^{-4}$ for our SIS mixer. According to the model in [2] this corresponds to an incremental gain compression of 1.8%. This is more than twice as much as the results of our measurements, but it is most likely that this discrepancy can be explained by the uncertainty of our rough estimates. Especially the assumption of a constant load impedance over the full bandwidth seems to be rather unrealistic. The small improvement of the linearity after the increase or decrease of LO power can be explained by the reduced mixer gain at these settings.

V. CONCLUSIONS

We determine the incremental gain compression of a 640 GHz SIS mixer with a perturbation technique in which a small modulated noise signal is added quasi-optically to different noise backgrounds. First measurements of an engineering model of the SIS mixer for the JEM/SMILES mission showed that the nonlinearity which is caused by a 300 K thermal background is in the order of 0.7%. The actual flight hardware can have a different characteristic because it contains an improved IF matching circuit [8] and different HEMT amplifiers. For that reason similar linearity tests are planned for the final JEM/SMILES receiver subsystem.

Our current measurements have an uncertainty in the order of ±0.1% because of the limited stability. One reason for this are the strong 1 Hz fluctuations caused by the cooler of the test facility. The real JEM/SMILES receiver has a better space qualified 4 K cooler which operates with a faster compressor cycle ($>$15 Hz) and which has been designed to minimize mechanical vibrations [9]. For that reason it can be expected that the linearity tests of the complete SMILES receiver can be done with a higher precision. Laboratory tests in a liquid Helium bath cryostat should be even more stable. Further improvements could be achieved by temperature stabilization of the diode detector.

The best way to overcome the stability problems is to use an automated switching mirror for changing the noise background T between hot and cold. This would allow to decrease the time constant of the Lock-In amplifier and to average the ratio of many cold/hot measurements. In our current setup this was not possible because the loads were replaced manually, but for the tests of the complete system a computer controlled switching mirror will be used.

The JEM/SMILES mission plan requires that the linearity of the SIS receiver is better than 1%. Our measurements have confirmed that the current mixer design fulfills this requirement. The linearity of the complete receiver in space will be even better than our results because of the sideband filter which is included in its optics. It will always terminate the image band on the cold sky, whereas the noise background was present in both sidebands during our laboratory tests.

REFERENCES

[1] D. Teyssier and M. Pérault, “HIFI calibration plan,” Tech. Rep. LRM-ENS/HIFI/PL/2000-001, Issue 1, SRON, Groningen, NL, Oct. 2003.

[2] A. R. Kerr, J. Effland, S. Pan, G. Lauria, A. W. Lichtenberger, and R. Groves, “Measurement of gain compression in SIS mixer receivers,” in *Proc. 14th International Symposium on Space Terahertz Technology*, (Tucson, AZ), Apr. 2003.

[3] SMILES Science Team, “JEM/SMILES Mission Plan, version 2.1,” tech. rep., Japan Aerospace Exploration Agency, Tsukuba, JP, Nov. 2002. available at http://smiles.tksc.jaxa.jp.

[4] T. Noguchi, S. C. Shi, and J. Inatani, “An SIS mixer using two junctions connected in parallel,” *IEEE Trans. Appl. Supcond.*, vol. 5, p. 2228, June 1995.

[5] A. R. Kerr, “Saturation by noise and CW signals in SIS mixers,” in *Proc. 13th International Symposium on Space Terahertz Technology*, (Cambridge, MA), Mar. 2002.

[6] Thomas Keating Instruments Ltd., “Space qualified tessalating THz RAM.” http://www.terahertz.co.uk/.

[7] K. Kikuchi, Y. Fujii, and J. Inatani, “Simple FTS measurement system for submillimeter SIS mixer,” *International Journal of Infrared and Millimeter Waves*, vol. 23, pp. 1019–1028, 2002.

[8] K. Kikuchi, S. Arimura, J. I. Y. Fujii, T. Suzuki, A. Iwamoto, and A. Yamamoto, “Impedance matching of 640 GHz SIS mixer in a high IF band of 11-13 GHz,” in *Proc. 16th International Symposium on Space Terahertz Technology*, (Göteborg, SE), May 2005.

[9] K. Narasaki, S. Tsunematsu, S. Yajima, A. Okabayashi, J. Inatani, K. Kikuchi, R. Satoh, T. Manabe, and M. Seta, “Development of cryogenic sustem for JEM/SMILES,” in *Proc. The Cryogenic Engineering Conference and the International Cryogenic Materials Conference*, (Anchorage, AK), Sept. 2003.