Results and Analysis of HIFI Band 2 Flight Mixer Performance

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***Abstract*— We present the flight mixers for Band 2 of the HIFI instrument on the Herschel satellite observatory [1], [2]. Three flight mixers are produced, tested and delivered. They are shown to be fully space qualified by environmental tests on identical prototypes. After subtracting the noise of the optics and external IF-components the RF-performance requirements for the receiver-noise inside the instrument ($T_{Rec} = T_{Mix} + 10$ K$/G_{Mix}$) of 110 K at 636 GHz and 150 K at 802 GHz are met for 75% of the band within an assumed error of $\pm$15 K in noise temperature. The IF-output power variation is well below 2 dB. The limits in performance of the fabricated devices are analyzed and compared with theory [3]. Possible noise mechanisms are discussed and estimated.**

The mixing elements are SIS-devices (single Nb/Al_2O_3/Nb-Junctions) with a current density of 13-14 kA/cm^2 with a NbTiN/SiO_2/Nb-matching circuit, which are fabricated at KOSMA [4], [5]. Waveguide environment and probe are designed by simulation with a 3D-simulation software, which is also used to investigate the detailed IF performance. The waveguide blocks and the IF circuits are also fabricated in house.

I. Introduction

In this paper we present the SIS mixers for band 2 of the HIFI instrument for the Herschel satellite observatory. The performance for HIFI is specified as 110-150 K input noise temperature over the 636-802 GHz band for the mixer and the low noise 4-8 GHz amplifier (T_{IF}=10 K) together. In addition to these performance requirements, the mixer design is subjected to numerous environmental constraints to insure the reliable operation of the mixer during test, launch and operation.

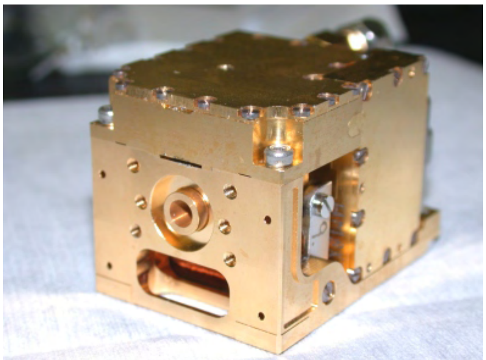

Fig. 1. Photo of mixer flight model hardware for HIFI frequency band 2.

II. Mixer Design

As part of a space project the mixer unit has to comply to the given interfaces of the rest of the instrument. The performance requirements for the different components of the mixer *especially RF- and IF-performance* have to be met. At the same time all components have to fulfill specific environmental requirements: thermal hardness during bake-out before launch, mechanical stability during launch and reliability during operation in space etc. In order to achieve the requirements for each single component of the mixer a modular mechanical design was applied. So one component could be tested, improved or exchanged without a complete redesign of the entire mixer.

A. Mechanical Design

The whole mixer has to fit into an envelope of $32 \times 32 \times 45$ mm^3. The maximum allowed mass is 80 g. A sketch of the major components is given in figure 2.

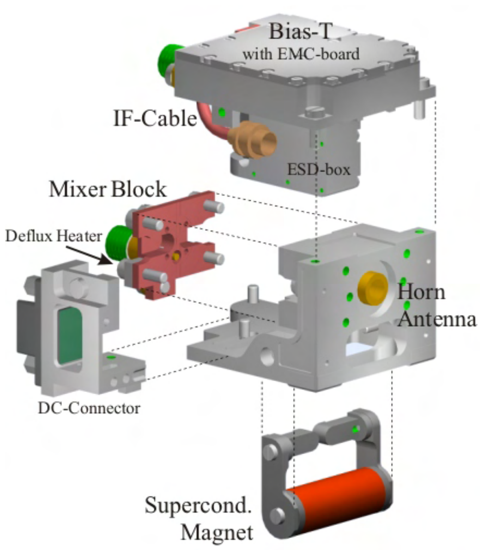

Fig. 2. The components of the mixer are mixer block with heater and SIS-device, horn antenna with bracket, bias-T with ESD- and EMC-protection, DC-connector and super-conducting magnet.

The mixing SIS-device is in the substrate channel across the waveguide of the the copper fixed tuned waveguide mixer block. Details of the block and the mounting of the SIS-device are given in [6]. The mass of the block is reduced to meet the HIFI mass budget. For selection of the devices, the performance of an SIS-device could first be tested in its mixer block in another test mixer environment. The mixer blocks with the best devices were assembled with the flight hardware.

The mixer block and its waveguide is connected and positioned to the corrugated feed horn and its bracket via dowel pins and screws. The horns were fabricated by Radiometer Physics [7] for a center frequency of 720 GHz (for characterization see [8], [9]). Fabrication tolerances in the outer reference cylinder of the horns were compensated by adapting a dedicated bracket for each horn.

The mixer block is connected to the bias-T with an SMA connector and semi rigid cable. In the bias-T the DC connections are protected against electro-static discharge (ESD) and shielded against electro-magnetic interference (EMI). The bias-T consists of two compartments: one compartment (on top of the mixer) for the DC-connection to the semi rigid cable with the EMI-protection and a second compartment besides the mixer block with a circuit for protection against ESD from the DC-connector to the sensitive mixer device.

To suppress the Josephson effects in the SIS-junction a superconductive magnet is used. The maximum allowed current here is 10 mA, which leads to a magnet of 10,000 turns of 70 μm thick NbTi copper cladded wire. The pole pieces are out of pure iron ($\geq$99.9 %).

The second DC-connector (front left in figure 2) provides the electrical connection for the mixer deflux heater, consisting of a thermally well connected 1.5 kΩ SMD resistor, and the magnet current.

B. RF-Design

The SIS-device is located in a substrate channel perpendicular to the waveguide. An asymmetric stripline waveguide probe couples the radiation to stripline modes and is integrated with an RF-blocking filter. The impedance of the waveguide

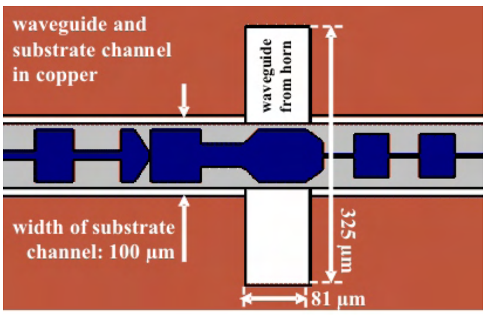

Fig. 3. Schematic concept of the asymmetric stripline waveguide probe, optimized for low waveguide impedance ($\approx$ 30 Ω).

probe is determined and optimized by a full electro-magnetic 3-dimensional time domain analysis software [10]. A sketch of the optimized waveguide model is given in figure 3.

To couple the radiation from the waveguide in the SIS-junction, a three step transformator as resonant matching circuit is used. It transforms the waveguide impedance to the lower impedance of the junction and compensates the intrinsic capacitance of the junction.

As mixing element in the HIFI frequency band 2 (636–802 GHz) superconductor-isolator-superconductor junctions (SIS) are used. The layout of the devices is depicted in figure

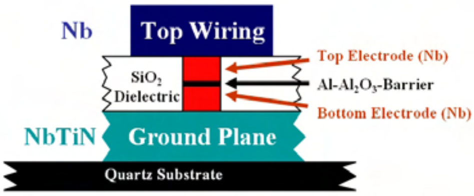

Fig. 4. Cross section of an SIS junction of a HIFI mixer chip

4. As junction electrode material in this frequency region the well known material Niobium can still be used. The Nb/Al-Al_2O_3/Nb junction is embedded in an NbTiN/SiO_2/Nb resonant microstrip tuning circuit, processed on a fused quartz substrate.

For a good coupling a lossless stripline would be ideal. A superconductor with a gap-frequency well above the frequency band 2 is NbTiN. Optimum coupling with negligible losses in the stripline would be with NbTiN as ground-plane and top-wiring. Because this causes heat trapping due to Andreev-reflection at the interface of the the Nb-electrode with the NbTiN-wiring [11], the top-wiring is made of Niobium despite the losses of this material above 700 GHz, which makes cooling of the Nb junction electrode via the top-wiring possible.

Aluminium top-wiring which could be used as an alternative for Nb shows a better conduction than Nb above 750 GHz, but would give a considerably worse performance below 750 GHz, and especially below 700 GHz. So for an optimum overall band performance Nb is the best choice. In addition Nb is also more rugged than aluminum as a top electrode material, which is an advantage for environmental testing. The NbTiN quality which is determined by the critical temperature and the DC resistivity at 20 K was improved compared to the process described in [4] by heating the substrate to 400°C during the reactive magnetron sputtering process of this layer.

The stringent requirements on the RF performance of the mixer demand in particular an accurate junction definition (size and alignment) in addition to a low loss integrated tuning circuit. Variations in the junction area shift the center of the frequency band, where the matching circuit is optimum. A variation in the junction width of Δl_{SIS}=0.1 μm, which is typical for UV-lithography, results in a shift of the frequency band of $\approx$15 GHz or a relative reduction in power coupling at a fixed frequency of $\gtrsim$30 %. With a relative bandwidth of 23 % and the stringent performance requirements for the mixers this means, a variation in junction width of Δl_{SIS}=0.1 μm results in a performance which is far from the specification (see figure 5). For a broadband matching there is a high priority to produce devices with a definite submicron junction area. This is achieved by the use of electron-beam lithography and

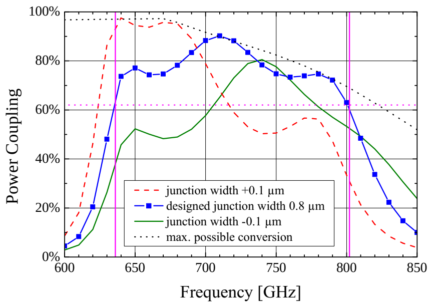

Fig. 5. Analysis of variation in junction width. A change of Δl_{SIS}=0.1 μm results in a strong shift of the frequency band. If e.g. the value of 62 % is assumed as the necessary power coupling to meet the specification the optimized matching circuit with a junction area of (0.8 μm)^2 is above this threshold for the whole band. If the junction width changes with Δl_{SIS}=±0.1 μm, for more than 50 % of the frequencies the power coupling is too low which results in higher noise.

a subsequent chemical mechanical polishing step, which is described in detail in [5].

The conduction of NbTiN and Nb was calculated after the theory of Mattis-Bardeen [12]. The power coupling is calculated from the surface impedances of the striplines including fringe effects [13] and step inductances [14] with KOSMA inhouse software, developed in the course of several years of experience. The calculated power coupling for an optimum broad-band matching circuit is already given in figure 5 (filled squares). Design parameters for the junction are a current density of 15 kA/cm^2 and a gap-voltage of 2.75 mV. Junctions are calculated for areas from (0.8 μm)^2 to (1.0 μm)^2.

C. IF-Design

The mixerblock and the bias-T are connected via SMA connectors and a 50 Ω semi rigid cable. So these two parts of the IF chain in the mixer unit can be optimized and measured separately. The IF path insde the mixerblock is shown in figure 6. The plot in Figure 7 shows the matching for the IF

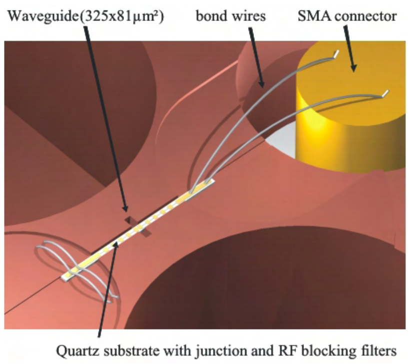

Fig. 6. The IF path in the mixerblock.

signal from the junction to the SMA connector calculated in a EM 3D simulation for different junction impedances. Reliable standard wire bonding of the mixerchip to the SMA still results

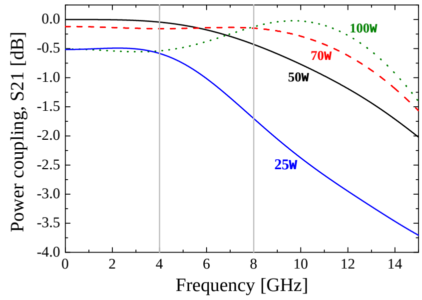

Fig. 7. Calculated IF coupling from the junction dynamic impedance to the SMA connector of the mixerblock.

in a good match up to approximately 10 GHz, provided the junctions dynamic impedance is between 50 and 100 Ω. The signal is then guided through a semi rigid SMA cable from the mixerblock to the bias-T circuit.

The main challenges in designing the bias-T were to find an extremely reliable solution for all connections avoiding single point failures, to provide good ESD protection, ample shielding and EMI filtering, and furthermore to place everything including bias- and IF-connectors mandatory on the backplane all in the tight envelope and weight constraints. The cable which ensures a flexible connection between the copper mixerblock and the aluminium bias-T box is directly flanged to the box. The inner conductor is connected via two thin strands to the microstrip line. This flexible connection assures stability under thermal and vibrational stress and saves the space and weight of another (SMA) connector.

To avoid damage by ESD while the mixer is integrated into the FPU all bias lines have RC filters in a 2nd separate compartment. In combination with additional microstrip filters they protect the mixer chip from EMI of other spacecraft instruments through the unshielded wiring in the HIFI dewar. The compartments need to be completely shielded with the exception of a tiny hole for the bias line to prevent crosstalk between the different filter sections.

All parts of the bias circuit are designed using analytical models, 3D simulation technique and network analyzer measurements of real models. A model of the bias-T with the critical SMA to microstrip transitions and EMI filtering circuits is shown in figure 8. The metal pillar between the bottom and the lid of the box shorts out a box resonance around 6.5 GHz.

III. Environmental and Performance Tests

Most of the environmental tests were made during the qualification process of the mixers with qualification models (QM), which are prototypes for the later flight models (FM). The IF- and RF-performance tests were made with the FMs.

A. Environmental Tests

To test the influence of EMI in a ”noisy” satellite environment and the shielding of the bias-lines from the IF-ouput by

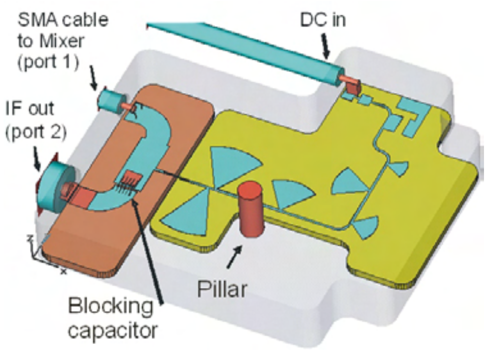

Fig. 8. 3D model used for simulations of the IF performance of the bias-T. The pillar in the box center suppresses a box resonance within the IF band.

the EMI filter inside the bias-T, the bias-lines where connected to unshielded cables of ≈1 m length and exposed to cw-radiation. The power coupling measured at the IF-output is given in figure 9. The coupling inside the IF-band is below

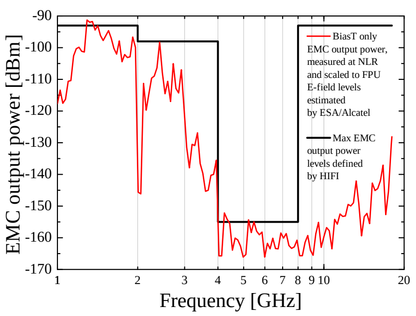

Fig. 9. RF coupling via unshielded bias-cables vs. frequency of cw-radiation

the allowed EMI levels.

The QMs were also were tested in a long 144 hours bake-out test at a temperature of 83 °C. The current density of the devices was reduced by ≈10 %. The mixer noise temperature did not change more than 10 K. Although the absolute error of the mixer noise temperature is 15 K, this difference value of 10 K with the same measurement setup and same correction terms for optics and IF-contribution is reliable. This change in mixer noise lower than 10 K is within the allowed tolerance.

As a test for the mechanical stability during the launch of the satellite a vibration-test at cryogenic (77 K) and room-temperatures with QM- and FM-mixers were made. At random and sine vibration levels the mixers did not show significant resonances.

B. RF-Performance

The three devices with the best RF-performance during the pre-tests were chosen and then tested in the FM-brackets with FM-bias-T at 2.9 K ambient temperature. From these three FMs FM1 and FM3 showed the best performance. FM2 is used as an attrition mixer. Here only the results of FM1 and FM3 are presented.

1) FTS-Measurement: To characterize the RF-bandpass of the mixers Fourier-Transform-Spectrometer measurements were made with a commercial instrument [15]. The measurements were made in voltage-detection mode with a 75 μm mylar beamsplitter which was characterized before with a separate internal DTGS-detector. The measured coupling for FM1 and FM3 corrected for the transmission of the internal beamsplitter is shown in figure 10. The lower band edge of the

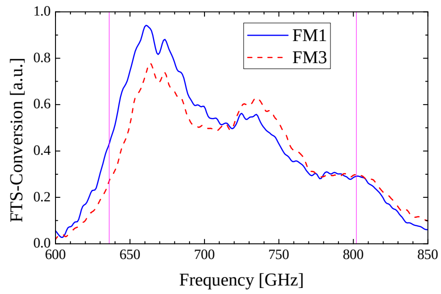

Fig. 10. FTS-conversion vs. frequency, corrected for FTS-beamsplitter

FM3 is shifted to higher frequencies by $\Delta\nu$ ≈10 GHz with respect to the FM1. One can clearly see that the structure is similar to the designed curves in figure 5).

2) Heterodyne Measurements: The receiver noise temperature of the system was measured with a standard hot-cold-setup (hot: 295 K, cold: 77 K black-body load). As local oscillator frequency-locked solid-state LOs were used [7]. To couple load signal and LO-radiation into the 2.9 K dewar, a 12 μm mylar beamsplitter was used. The dewar window is a 0.44 mm teflon-window. As IR-shield one layer Zitex G 108 (thickness 0.20 mm) was used [16]. The transmission of the three optics components was characterized with the FTS. For the beamsplitter under 45° the transmission was measured polarization dependent with a polarization grid.

A typical hot-cold-measurement is shown in figure 11. At

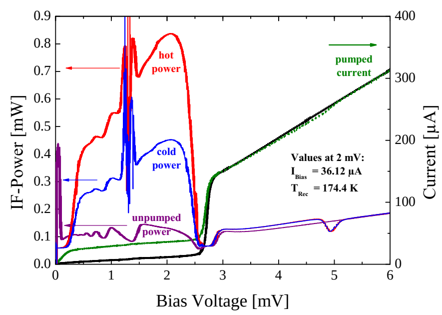

Fig. 11. IF-power and device current of FM1 at 642 GHz vs. bias-voltage

1.3 mV in the pumped IF-power one can see the Shapiro-steps which are not suppressed totally in this measurement.

The resulting receiver noise temperatures for FM1 and FM3 are shown in figure 12 (top). The shift in the frequency band

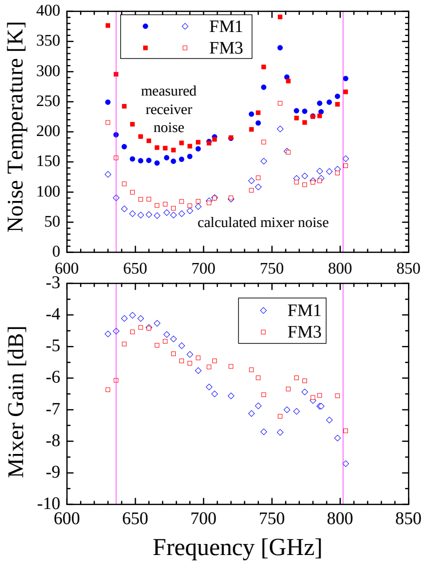

Fig. 12. Measured receiver noise for FM1 and FM3 (filled squares and diamonds) and calculated mixer noise and mixer gain (open squares and diamonds). The increased noise at ≈750 GHz is a result of the water absorption in the non-evacuated signal path. This feature is not seen in the evacuated FTS-measurement (figure 10).

of FM3 with respect to FM1 which was already seen in the FTS-measurements is reproduced in the noise measurement. The corrections for the optics vary from 48 K to 58 K with RF-frequency. The corrections for the IF-chain (5.5 K) are obtained from a hot-cold measurement of the IF-chain with a 50 Ω resistance load and a standard Schott-noise fit of the unpumped IF-output power vs. bias-voltage. All calculations were made after the Callon-Welton formula (see [17]).

The baseline for the HIFI-project is defined for a receiver assuming optics with 100 % transmission and IF-contribution of 10 K. The resulting receiver noise temperature ($T_{Rec,HIFI} = T_{Mix} + 10\ \mathrm{K}/G_{Mix}$) is plotted and compared with the baseline in figure 13. The error of these values is ±15 K because of

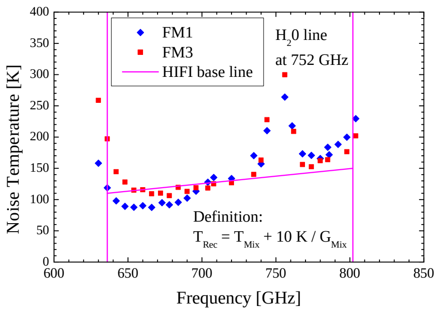

Fig. 13. Calculated HIFI receiver noise assuming 10 K IF-noise vs. LO-frequency and HIFI baseline.

the tolerances of accuracy in the measurements of the optics- and IF-contribution. Within this error the HIFI receiver noise for the to FM-mixers matches the baseline for 75 % of the frequency band.

C. IF-Performance

The IF-performance of the bias T was separately measured with a network analyzer at room temperature. The measured values are shown in figure 14. One sees a very good agreement

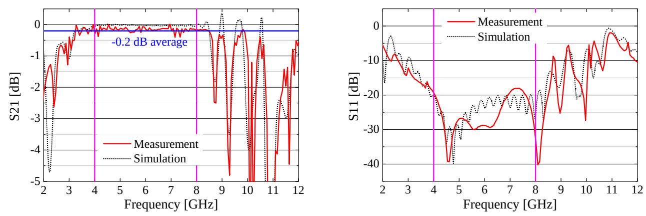

Fig. 14. Transmission (left) and reflection (right) of bias-T. Measurements with network analyzer as solid line, 3D simulation (CST Microswave Studio) as dashed line.

of the measurements with the 3D-simulated data. The contribution of the bias-T to the IF noise, measured separately at 3K, is lower than 1K.

During the RF-measurement with the mixers also IF-resolved measurements with a spectrum-analyzer were made. Hot and cold IF output power were measured as a function

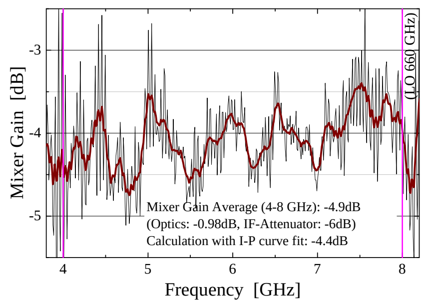

Fig. 15. Calculated mixer gain vs. IF-frequency measured with spectrum analyzer. The IF-ripple is well below 2 dB. The bold line is an average over the data to eliminate random noise.

of IF-frequency. For the measurement at an LO-frequency of 660 GHz the calculated mixer gain is plotted in figure 15. The maximum ripple over the IF-band is found by this method to be well below 2 dB for the whole RF frequency band.

IV. Noise Analysis

After comparison of the FTS-data, mixer noise and mixer gain with the calculated conversion using the measured material parameters (ρ=80 $\mu\Omega$cm and T_c=13.8 K), including the measured dc-values for normal resistance R_N and gap voltage V_{Gap} a current density of 13–14 kA/cm^2 is obtained for both FM devices. The shape of the coupling curves only fits if an additional geometrical shift of the matching circuit with respect to the SIS-junction of Δl=+0.5 μm and a broadening

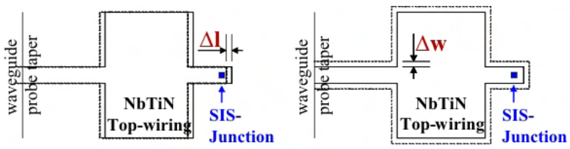

Fig. 16. Influence of variation in fabrication: absolute positioning accuracy Δl, stripline broadening Δw.

of the striplines of Δw=+0.2 μm is assumed (for definition see figure 16). These values are in the reasonable range for the fabrication tolerances. In this analysis the parameters are not fully determined. For example a higher current density j_c can be compensated by a lower Δw and vice versa. But after reviewing photographs of devices from the same row of the batch the given values are reasonable.

Based on this analysis an embedding impedance can be estimated for both devices and the mixer noise be calculated from the DC voltage-current characteristics after Tucker's theory [3]. The results are given in figure 17. Here the

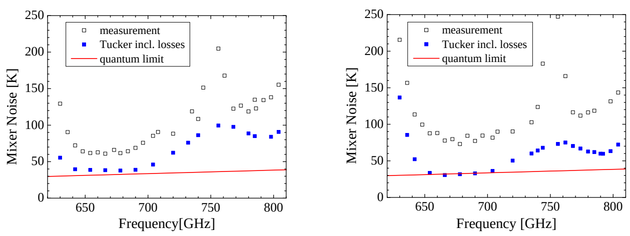

Fig. 17. Mixer noise of FM1 (left) and FM3 (right) after Tucker's theory (filled squares) and values from measurement (open squares).

pump power levels are taken to comply with the optimum levels in the measurement, which complies with the optimum theoretical power-levels. The band edges agree quite well in measurement and theory, but the absolute values of the noise do not comply with the measured values. There are several possible reasons for the discrepancy. According to [18] there can be a factor of 1.5 in mixer noise temperature because of multiple Andreev reflection in pinholes for this type of device (ν_{LO}=700 GHz, j_c=13–14 kA/cm^2, R_{subgap}/R_N=9). This would to a great extent explain the big difference from theory to the measurement. In addition to that the quality data for the stripline materials Nb and NbTiN are measured dc at single layers, not striplines. Losses at the interfaces and possible partial step coverage are not included.

V. Conclusion

Three mixers were fabricated, assembled and tested by KOSMA for the HIFI band 2 and delivered to the project. The modular design of the mixers is favorable to testing optimizing and space qualification of separate components within limited time schedule. The RF-baseline is met for 75 % of the frequency band. Losses and additional noise yield a factor $\lesssim$2 of the theoretically possible mixer noise. So additional analysis is necessary and optimization of the devices is still possible for future projects. The IF-performance fulfills the requirements.

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