Development of the HIFI band 3 and 4 mixer units

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We describe the current status of the HIFI mixer units for Band 3 and Band 4. The mixer units cover the 800-960 GHz and 960-1120 GHz frequency range with a 4-8 GHz IF frequency band. The major requirements and design drivers are presented. Functional tests of the magnet, the de-flux heater and the corrugated horn were performed. Details of the mechanical design of the mixer units and the assembly procedure are described.

1 Introduction

The Herschel Space Observatory (launch date 2007) will fly two bolometer instruments (PACS and SPIRE) and the heterodyne instrument HIFI [1]. An international consortium led by the PI institute, SRON, is building HIFI [2]. Within HIFI, 7 frequency bands cover the spectral range from 480-1250 GHz (SIS mixers) and 1.41-1.91 THz (HEB mixers). During observations a single frequency band will be operational. SRON is also responsible for the development of the mixer units for band 3 (800-960 GHz) and 4 (960-1120 GHz). Each of these bands contains two tunerless waveguide mixers to measure both signal polarizations simultaneously. The mixer units are mounted on a 2 K platform in a mixer console that thermally isolates the mixer units from the Focal Plane Unit (10 K ambient temperature). Within the Focal Plane Unit, each of the mixer units is connected to a 4-8 GHz IF chain consisting of two isolators (one at 2K and one at 10 K) a low noise first stage IF amplifier close to the mixer unit, and a common second stage IF box. The second stage IF box provides further amplification, signal equalization, and finally power combining of the 14 separate IF channels into four coax lines that run between the cold and warm (outside the dewar) IF back-end. In the back-end a Wide Band Spectrometer and a High Resolution Spectrometer are available for IF spectral analysis. The LOs for the 7 bands are located in the LO-box, mounted on the outside of the dewar, and injected by either a wire-grid beam splitter (bands 1 and 2) or a Martin-Pupplet diplexer. [3]

During observations, the instrument will run in an autonomous mode. Optimal settings of the mixer units (bias voltage, magnet current, LO power) therefore have to be available from look-up tables. Further details on the HIFI focal plane unit are given in a paper by Jackson et al. [4]

The mixer unit development program is currently in the Qualification Model phase, where extensive environmental testing will prove the flight worthiness of the units. In this paper we present the current status of the mechanical layout of the mixer unit and experimental results of its functional behavior. Environmental qualification testing will be done in near future and may give rise to design changes in the mixer unit presented in this paper. Details on the current performance status and the SIS device design are presented in a separate paper by Jackson et al. [5,6].

2 Requirements

The specific requirements for a space mission and the unique opportunity for a space based heterodyne observatory determine to a great extent the performance and mechanical design drivers for the mixer units. A summary of the design drivers is given in Table 1.

T_{mix} DSB	Band 3		Band 4	
Frequency	*800 GHz*	*960 GHz*	*960GHz*	*1120 GHz*
Baseline	119 K	158 K	158 K	190 K
Goal	99 K	129 K	129 K	151 K

Sensitivities, excluding contributions from IF chain and optics losses

•Withstand shelf life, bake-out, launch and in-orbit operation (9 years)
•Mass < 75 grams
•Envelope 32x32x45 mm
•IF range 4-8 GHz, ripple < 2dB/1 GHz
•De-flux heater operating at current < 15 mA
•Magnet current < 10 mA for second minimum in the Fraunhofer pattern
•Beam quality
•Optical alignment tolerances (goal): x,y: 42 μm, tilt 0.2°
•ESD protection, EMC shielding
•Bias circuit isolation > 30 dB in IF range

Table 1 Summary of the main requirements of the HIFI band 3 and 4 mixer units

The two main requirements for the instrument are reliability and sensitivity. Note that the challenging goal sensitivities of the mixer units given in Table 1 are the sensitivities of the mixer unit only, without noise contributions from the optics and IF. Constraints on mass, envelope, magnet current, and heater current and are mainly determined by the need to minimize the dissipation and heat load on the 2 K and 10 K level. The choice of materials and procedures in the assembly of the unit is driven by the environmental conditions of the instrument during shelf-life (several years), bake-out (80 degrees for 72 hrs), thermal cycling (approximately 25 times), launch (vibration levels, 20 G rms in qualification) and in-orbit operation (>3 years). Procedures and materials commonly used in ground-based and laboratory receivers are not compatible with these environmental conditions (e.g. silver paint or low temperature crystal bond).

The instrument assembly and spare unit replacement philosophy determine the alignment tolerance on the position of the optical beam in the mixer unit. To allow for mixer unit replacement within the instrument (due to failure or significant performance improvement), a 'blind' replacement, relying on mechanical interfaces only, is foreseen. There are no adjustable mirrors within the instrument (mirrors will be shimmed once during assembly).

To allow the use of a magnet current look-up table it is necessary to be able to remove trapped flux from the SIS device and superconducting electrodes. A de-flux heater that can warm up the superconducting layers above their critical temperatures (in Band 3 and 4 this is about 15 K) is therefore implemented.

The potential high levels of electromagnetic fields within the instrument (specified as 2 mV/m in 3-9 GHz range, 2 V/m outside this range) require that the mixer units have proper shielding for EMC, especially in the 4-8 GHz IF range. Protective circuitry to avoid ESD damage during handling and operation is also required.

3 Main features

The current design of the mixer unit is shown in Figs 1 and 2.

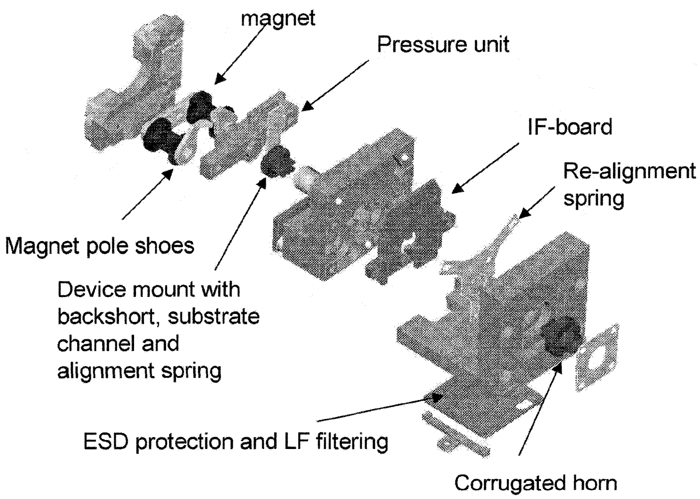

Figure 1 Exploded view of the mixer unit

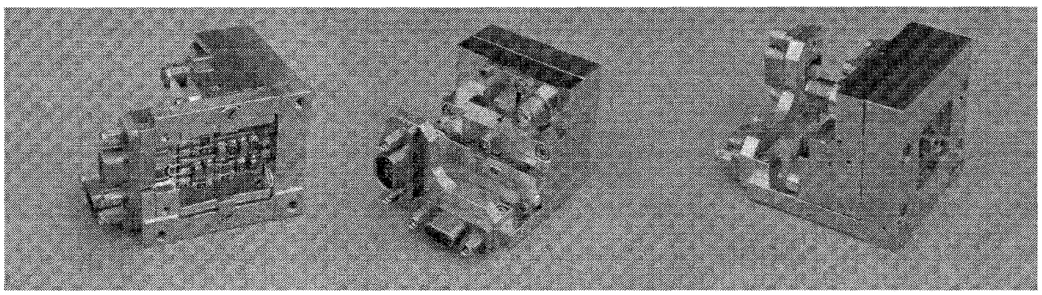

Figure 2 The QM prototype mixer unit

The unit consists of four sub-units:

- *The horn bracket.* This bracket holds the horn, the low frequency filtering and ESD circuit board, and the bias connectors (type: Cannon MDM 3401 9 pins). Also on the horn bracket are the mechanical reference planes that define the position of the bracket on the mixer console. The ESD/EMC filtering board is held in place with two aluminum springs. The board for the flight mixers will be made from alumina (FRP in the development unit shown here).
- *The IF-box.* This box houses the magnet, the IF circuit board, an auxiliary PCB, and the IF output connector (Radiall female bulkhead receptabel). The alumina IF circuit board is clamped with 2 Vespel springs into the housing
- *The device mount.* The SIS device and the heater are mounted in the device mount. Attached to the device mount is a leaf spring that is used for alignment purposes
- *The pressure unit.* This unit holds a pressure plate that is pushed forward against the device mount. Releasing a stack of washer springs inside the pressure unit applies a controlled pressure to the waveguide/device mount interface.

3.1 Corrugated horn

The mixer unit uses a corrugated horn antenna, tapering down to a reduced height waveguide of 300x75 μm (Band 3) or 240x60 μm (Band 4). The horn design is equal for all bands (except for a scaling factor). For the band 3 horn (with a center frequency of 880 GHz) the aperture radius is 1.6 mm and the horn slant length is 9.8 mm. At 880 GHz the far field divergence angle is 8.46 degrees and the waist size is 0.729 mm. The band 3 and 4 horns are currently being fabricated at RPG and Thomas Keating. Results of amplitude measurements on an RPG horn at 890 GHz are shown in Figs. 3 and 4. The experiments show that horns with a well predicted and symmetric beam pattern can be fabricated at these high frequencies.

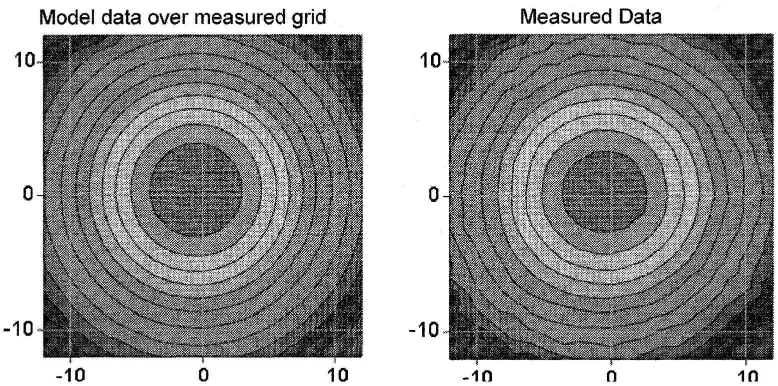

Figure 3 Model and measured data for a band 3 horn at 893 GHz

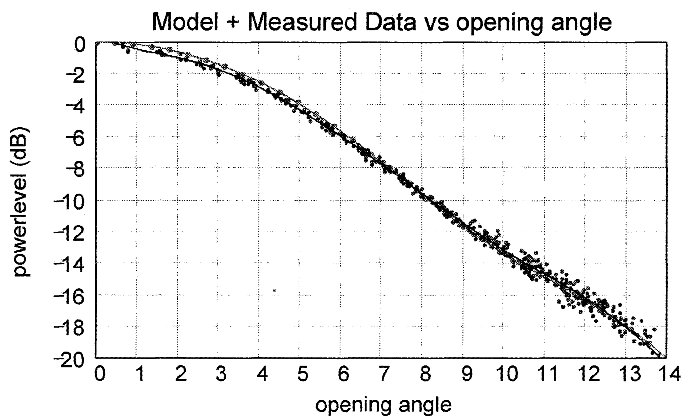

Figure 4 Comparison of model and experimental data of a band 3 horn at 893 GHz

3.2 Magnet

The magnet consists of two superconducting coils and a (multi-element) core of Vacuflux 50. The flight model coils will be fabricated using an ortho-cyclic winding technique by which the 64 μm diameter wires (fabricated by Supercon) on the coil are packed as densely as possible. The gap between the pole pieces at the position of the device is 1 mm. A 10 mA magnet current results in approximately 400 Gauss at the junction position. The amplitude of the Josephson super current versus magnet current for a single junction (approximately 1x1 μm) device is shown in Fig 5. The cause of the hysteresis has not been identified yet.

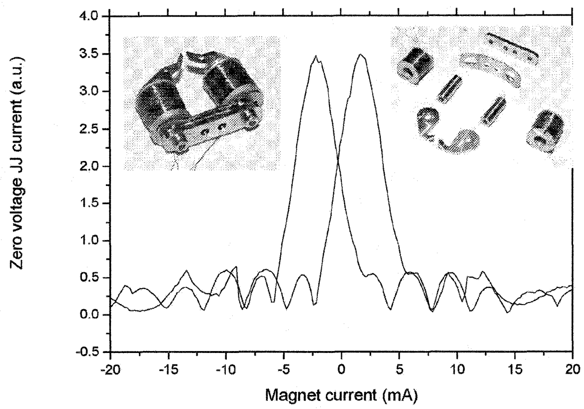

Figure 5 Zero-voltage supercurrent versus magnet current for a single junction device. The insets show the magnet parts and assembly

The best noise performance has been obtained with twin junction devices, with a 400 nm aluminum top electrode. To reduce the DC resistance of the top electrode we have added a 200 nm layer Nb on top of the aluminum. Due to proximity effects of the Nb on the Al this has the undesirable side effect that the two junctions form a SQUID loop. The super current versus magnetic field dependence for the twin junction device therefore shows a SQUID behavior (a rapid modulation on top of a Fraunhofer pattern). This makes the mixer unit very sensitive to magnetic field changes and flux trapping. Figure 6 shows an example of the supercurrent versus magnet current behavior of a twin junction device measured in a time span of an hour, before and after application of several heat pulses for flux removal. The magnetic field dependence varies considerably between the measurements. As one can see it will be difficult to give a single value magnet current for optimum Josephson effect suppression. Removing the top layer Nb locally, or not applying the extra Nb layer at all in future device fabrication runs, will avoid the SQUID type behavior of the device.

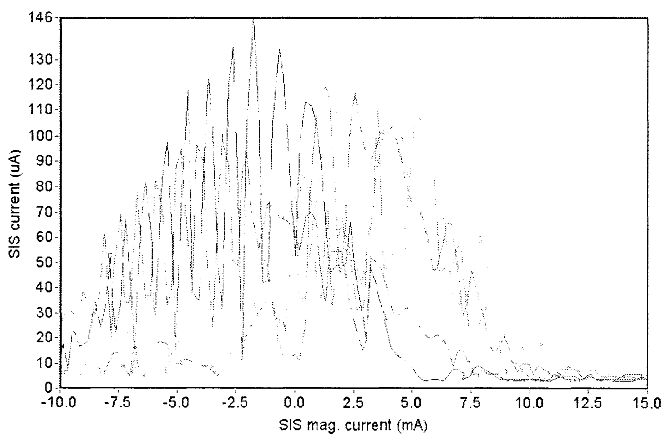

Figure 6 Magnetic field dependence of the zero voltage supercurrent in a twin junction device, after application of several de-flux heater pulses

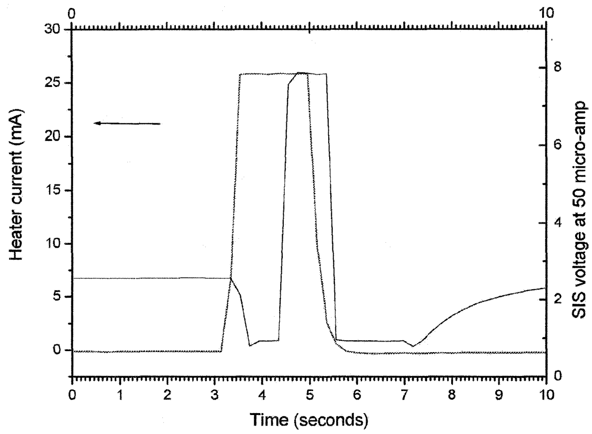

Figure 7 Heater current and junction voltage as a function of time.

3.3 De-flux heater

The de-flux heater consists of a 490 Ohm miniature resistor mounted with Apiezon T vacuum grease in a hole in the device mount. The heater resistor is in close proximity to the junction. To measure the heater characteristics we bias the device at a fixed current at the gap voltage.

A typical heater current and junction voltage versus time is shown in Fig 7. After applying the heater current (at t = 3 s) first the gap voltage decreases from 2.7 to 0 mV, then the Nb of the junction becomes normal conducting (at t = 4 s, T=9.2 K) and finally (at t = 4.3 s) the temperature reaches the transition temperature of the NbTiN. This is observed as a sudden increase of the device resistance because the NbTiN RF filter is no longer superconducting. The typical energy needed for heating the device to 15 K is 300-600 mJ. The actual effect of the de-flux procedure still has to be investigated in further detail. One has to insure that during cooldown no remnant magnetic fields are present which again could cause flux to be trapped.

3.4 IF circuit

The lay-out of the 625 μm thick alumina IF board and measured results of the bias-T isolation are shown in Fig. 8. The bias-T provides a 40 dB isolation between the DC and IF port within the 4-8 GHz IF range. The microstrip IF line is connected to the SMA output connector and the device via wire bonds. A 10 pF capacitor is used for DC blocking. We are currently investigating a planar 4-8 GHz bandpass filter for this purpose.

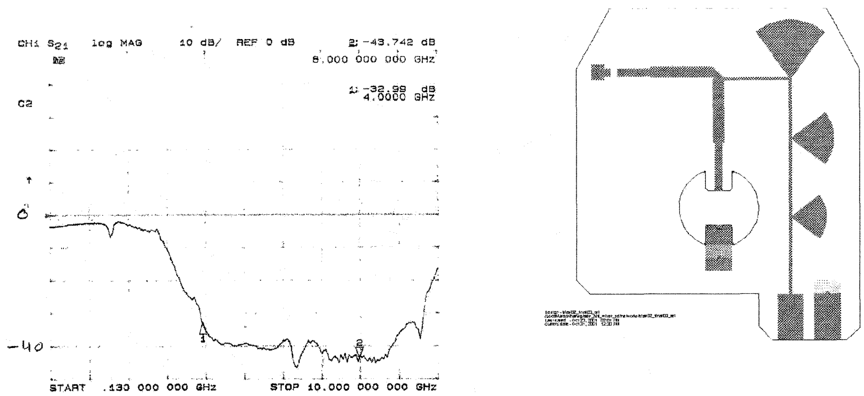

Figure 8 Lay-out of the bias-T circuit and the measured isolation of the bias-T.

3.5 ESD and EMC filter circuit.

An ESD and low frequency EMC filtering circuit is located in the bottom plate of the mixer unit (see Figs 2 and 9). The ESD circuit provides a 1000x protection. ESD tests on sample devices showed DC breakdown voltages in the range of 0.6 to 1.3 V.

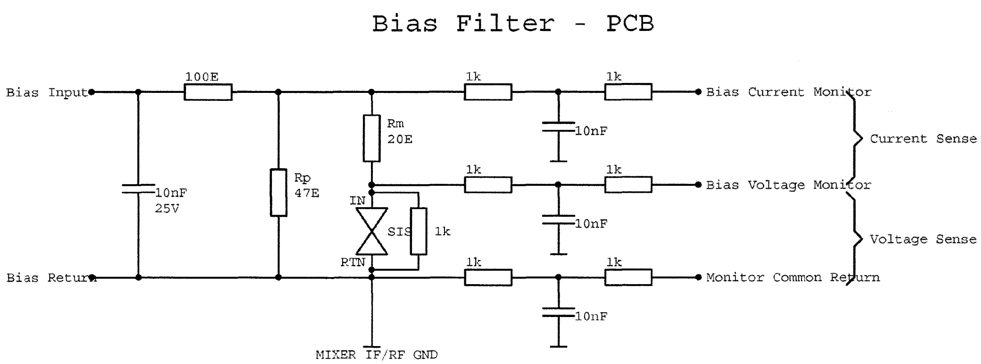

Figure 9 Schematic of the junction bias circuit, providing ESD and low frequency EMC protection.

4 Assembly procedures

The manufacturing and assembly procedures are chosen to comply with the environmental (e.g. aging, vibration, thermal cycling) and cleanliness (outgassing) requirements of a satellite instrument. Special attention is paid to the robustness of electrical interconnects (e.g. IF connector to IF board), electrical components, and component mounting methods with respect to thermal cycling and thermal bake-out.

4.1 Alignment:

We make use of in-situ alignment of the device mount to the waveguide of the corrugated horn. To do so, we attach the leaf spring on the device mount to a custom made x-y stage and position the device mount while looking down the corrugated horn with a 100x magnification (see Fig. 10). After alignment, a spring (a stack of spring washers) inside the pressure unit is released and the device mount is pressed against the horn. The leaf spring attached to the device mount is then locked in position to the IF-box. This alignment method simplifies the manufacturing of the device mount considerably, since there is no need to position the waveguide and substrate channel very accurately within the device mount. Furthermore it adds flexibility in the device mounting procedure and IF design, since we do not need dowel pins or screws in the vicinity of the device. The IF-box and horn bracket are positioned with respect to each other by means of a three point alignment, making use of three alignment spheres in the IF box, and a Y-shaped alignment spring with three slits in the horn bracket (Fig. 10). The realignment accuracy of this method is better than 5 μm.

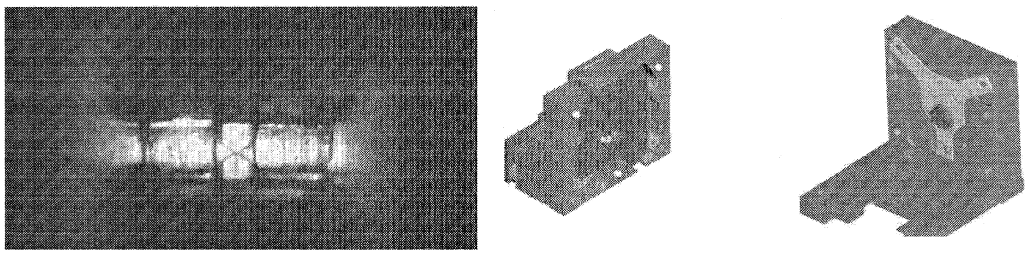

Figure 10 View of the device mount to waveguide(300x75 μm) interface as seen through the corrugated horn. Note that waveguide in the horn is slightly bigger than the waveguide in the device mount. The alignment of the horn bracket to the device box is defined by three spheres in the IF box, and an alignment spring with three slits in the horn bracket.

4.2 Device mounting

In our mixer designs at lower frequencies SIS devices are mounted into the device mount substrate channel with (super)glue, and electrical contact is made via silver paint or wire bonding on the device substrate. Direct bonding of 17 μm wires to the 40 μm contact pads on the thin (25 μm) substrates turns out to be a major cause of failure in the assembly procedure of the HIFI mixer units. We therefore develop an alternative mounting method in which the electrical contact to the device is made via silver epoxy (Epotek H20). The device is mounted with the silver epoxy on a gold patterned alumina carrier. The carrier is then mounted with Scotchweld 2216 to the device mount. Both Epotek H20 and Scotchweld 2216 have a flight record. Multiple wire bonds are used for the electrical contact from the contact pads on the carrier to IF-board circuitry (see Fig 11).

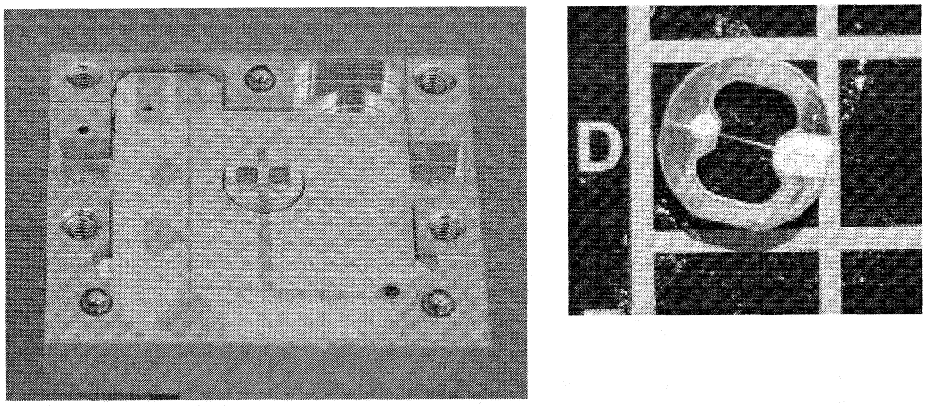

Figure 11 The IF box, with a (sample) alumina IF board and the device mount with an alumina mounting ring. On the right a prototype alumina mounting ring with a junction mounted with silver paint. .

During the test phase we make use of silver paint for the electrical contacting and (thermal) wax for the carrier mounting. The device and device carrier are easily removed from the device mount. This gives us the opportunity to characterize the device performance in a test unit and use the flight model mixer units only after a device has been selected.

5 Performance status.

The receiver Noise Temperature versus RF and IF frequency of one of the tested band 3 mixer units are shown in Figs 12 and 13. The instantaneous RF bandwidth observed in FTS and heterodyne measurements is sufficient to cover the 160 GHz HIFI specification, although this device is tuned too high in frequency to cover the actual band 3 frequency range. The overall

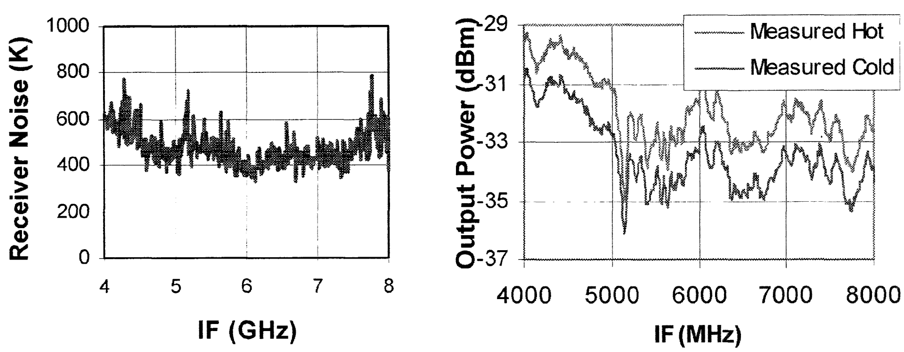

Figure 12 Noise temperature and IF output power for hot and cold input signals as a function of IF frequency

receiver noise temperature ranges from 400 to 1000 K DSB. The receiver noise temperature in HIFI will be considerable lower than our laboratory receiver, since HIFI will operate with a 10 K cooled diplexer and without vacuum windows or heat filters in the signal path. After correction for the optics losses (a room temperature beam splitter and vacuum window) the noise temperature ranges from 230-500 K. The variation of noise temperature within the 4-8 GHz IF band is still too large. We attribute the variations to the rather long wire bonds used for contacting the SIS device to the ground and signal line of the IF board.

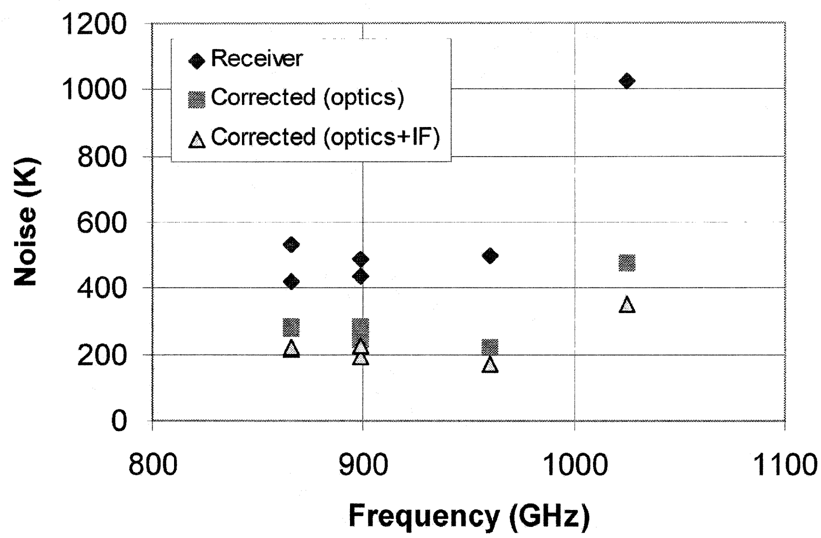

Figure 13 Receiver and corrected noise temperatures of a prototype band 3 mixer unit

5.1 Summary

In summary we have presented the current status of the band 3 and 4 mixer units for HIFI. The mixer unit is complying with the mechanical interface requirements. Measurements on the beam quality of the corrugated horn, the RF sensitivity in band 3 and the mixer unit bandwidth are very promising. The sensitivity at upper end of the band 4 has to be improved. Noise temperature variations within the 4-8 GHz IF bandwidth are still too large and the IF-output coupling circuit has to be optimized. The mixer magnet and de-flux heater are operating close to the required performance.

5.2 References

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