Performance of the HIFI Flight Mixers

Gert de Lange[1*], Jean-Michel Krieg[2], Netty Honingh[3], Alexandre Karpov[4], and Sergey Cherednichenko[5]

[1]SRON Netherlands Institute for Space Research, Groningen, the Netherlands

[2] Observatoire de Paris, LERMA, Paris, France

[3]Universität zu Köln, Physikalisches Institut, KOSMA, Köln, Germany

[4]California Institute of Technology, Pasadena, CA 91125, USA

[5]Chalmers University of Technology, Göteborg, SE-41296, Sweden

* Contact: gert@sron.nl, phone +31-50-363 4074

***Abstract*— We summarize the technology and final results of the superconducting heterodyne SIS and HEB mixers that are developed for the HIFI instrument. Within HIFI 7 frequency bands cover the frequency range from 480 GHz to 1910 GHz. We describe the different device technologies and optical coupling schemes that are used to cover the frequency bands. The efforts of the different mixer teams that participate in HIFI have contributed to an instrument that will have unprecedented sensitivity and frequency coverage.**

I. INTRODUCTION

After several years of development and qualification the HIFI instrument for the Herschel Space Observatory (HSO) is now in the final stage of verification. The launch of HSO together with Planck is scheduled for early 2009. The instrument has been cooled down to operating temperatures and will have no further thermal cycling. The current performance of the instrument can therefore be considered final. Once in orbit Herschel will provide a unique window to the sub-millimeter and THz frequency range. This frequency range is largely obscured for ground based astronomy due to the presence of water vapor in the earth's atmosphere. Herschel/HIFI will therefore make it possible to do detailed spectroscopic studies of water lines in the star forming regions of our galaxy. The Herschel Space Observatory will fly two cameras/medium resolution spectrometers (PACS and SPIRE) and the heterodyne instrument HIFI ([1]-[6]). An international consortium led by the PI institute, SRON, is building HIFI. Within HIFI, 7 frequency bands cover the spectral range from 480-1250 GHz (SIS mixers) and 1.41-1.91 THz (HEB mixers). In this paper we first present the general HIFI configuration and the specifications of the mixers. The subsequent sections describe the mixer design for each HIFI band. We then give a brief description of the sensitivity measurements of the mixers within the HIFI instrument.

II. GENERAL SPECIFICATIONS AND MIXER TECHNOLOGY.

A. HIFI configuration

Each of the mixer bands within HIFI contains two 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 SIS 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 HEB mixers have an IF chain of 2.4-4.8GHz and no isolators. The second stage IF box provides further amplification, signal equalization, and finally power combining of the 10 separate SIS mixer and 4 HEB mixer 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. 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 or simple optimization routines.

B. Mixer technology and specifications

Within the HIFI consortium 6 groups have contributed to the delivery of the 7 mixer bands. The institutes are listed in Table 1. Within the 460-1910 GHz frequency range different technologies had to be employed to achieve the most sensitive mixers. For frequencies up to 1250 GHz SIS mixers are used, for the two highest frequency bands phonon-cooled HEB mixers are used (Ph-HEB). SIS mixers have a better noise performance and higher IF bandwidth than HEB mixers, but the maximum operating frequency of SIS mixers is currently limited to about 1.5 THz. Furthermore the HEB mixers need much less Local Oscillator power. This was of crucial importance to obtain sufficient LO power at the highest frequency bands. A drawback of the HEB mixers is the limited IF bandwidth. At the start of the project there were indications that diffusion cooled HEB mixers could achieve the 4-8GHz IF bandwidth, but this technology turned out not to be mature enough to be used within HIFI.

Within the SIS bands also different technologies have been used to achieve the optimum performance. Main driver for this is the superconducting gap frequency of the materials used. Below the gap-frequency (which is about 700 GHz for niobium) a superconductor acts as a perfect lossless material. Above the gap-frequency a superconducting electrode may act as a poor conductor with high losses. Furthermore at frequencies above twice the gap-frequency the SIS junctions do not operate as mixers anymore. Because of this, the SIS bands have used a variety of electrode materials and junction topology. A summary of the technology is given in Table 1. One further main variety within the HIFI bands is the optical coupling scheme. Up to band 5 waveguides and corrugated horns are used for the coupling of signal and LO, bands 5 and 6 use a quasioptical coupling with a Si lens and a twin slot antenna. In the integration of the mixers it was found that the optical alignment of the waveguide mixers could almost fully rely on the mechanical alignment references of the mixer units. The quasi-optical mixers needed more attention and some iteration of beam measurements and mechanical alignment adjustments. Also it is found that the beam profile of the QO mixers can be modelled very well, but that the manufacturing tolerances on the lens shape become very critical (at µm level).

TABLE I
OVERVIEW OF HIFI MIXER TECHNOGY

Band Institute	Freq. Range (GHz)	RF-coupling	Detector technology	Device technology:
1 LERMA	480 640	Waveguide/ Horn	SIS	Nb/AlOx/Nb Nb/Nb
2 KOSMA	640 800	Waveguide/ Horn	SIS	Nb/AlOx/Nb NbTiN/Nb
3 SRON	800 960	Waveguide/ Horn	SIS	Nb/AlOx/Nb NbTiN/Al
4 SRON	960 1120	Waveguide/ Horn	SIS	Nb/AlOx/Nb NbTiN/Al
5 CALTECH JPL	1120 1250	Lens/ Planar Antenna	SIS	Nb/AlN/NbTiNe-Nb/Au
6L CTH JPL	1410 1660	Lens/ Planar Antenna	HEB	NbN
6H CTH JPL	1660 1910	Lens/ Planar Antenna	HEB	NbN

Besides the sensitivity of the mixers, the ability of the mixers to withstand the on-ground test-phase, the launch (vibration levels!) and the operation in space are of crucial importance. Much time was spent to develop space-qualified manufacturing and assembly procedures. For example, the mixers are specified to have an internal bias and ESD protection circuit, and to fulfill strict alignment tolerances of the optical beam w.r.t. mechanical references. These requirements are necessary to assure a safe and reproducible integration of the mixer units into the HIFI Focal Plane Unit. The main operational specifications of the mixers are:

• Withstand shelf life, bake-out, launch and in-orbit operation (9 years)
• Mass < 75 grams
• Envelope 32x32x45 mm
• IF range SIS mixers: 4-8 GHz, ripple < 2dB/1 GHz
• IF range HEB mixers: 2.4-4.8 GHz, ripple < 2dB/1 GHz
• De-flux heater operating at current < 20 mA (SIS only)
• Magnet current < 10 mA for second minimum in the Fraunhofer pattern (SIS only)
• 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

The mixer groups have developed different approaches to fulfill these specifications. A common design is used as much as possible (e.g. corrugated horns, bias board manufacturing), but simple scaling of one common design is not possible. This is partly due to the in-house technological expertise of the mixer groups at the start of the project and partly to the mechanical specifications. For example, the band 1 horn is twice as long as the band 4 horn, but they have to fit within the same mixer envelope. This requires a different design of the magnet, which in turn requires a different design of the IF circuit board etc. All the different technologies that are used in the end have proven to be space-qualified.

III. BAND 1

The band 1 mixers are developed by LERMA, in collaboration with IRAM [7]. The band 1 frequency range is 480-640 GHz. The device technology is based on Nb/AlOx/Nb SIS junctions (Jc=10 kA/cm^2, area= 1 µm^2), with Nb electrodes. The on-chip tuning circuit is a twin junction design with an impedance transformer. Band 1 has the largest relative bandwidth of the HIFI mixers (30 %, vs. 10 % for band 5). To achieve this bandwidth the band 1 team has developed a new waveguide coupling structure that does not need a backshort cavity (see Fig. 1). This greatly facilitates the manufacturing and assembly of the mixer block, since there is no critical alignment between horn waveguide and backshort necessary.

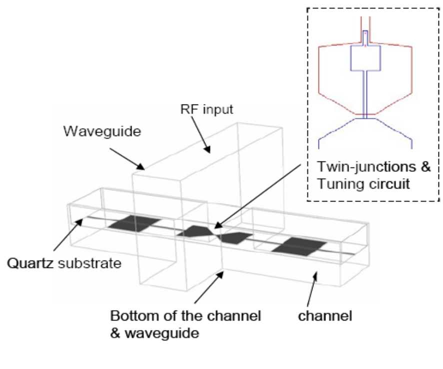

Figure 1 Band 1 mixer configuration with no backshort waveguide. The inset shows the SIS tuning circuit

Band 1 also used novel technologies for the IF output coupling (with a spring loaded bellow) and circuit board mounting (with metallized kapton).
Figures 2 and 3 show some details of the mechanical design. The final results of the sensitivity of one of the FM units as measured by LERMA are shown in Fig. 4. The sensitivity is excellent and well below the original specified baseline values.

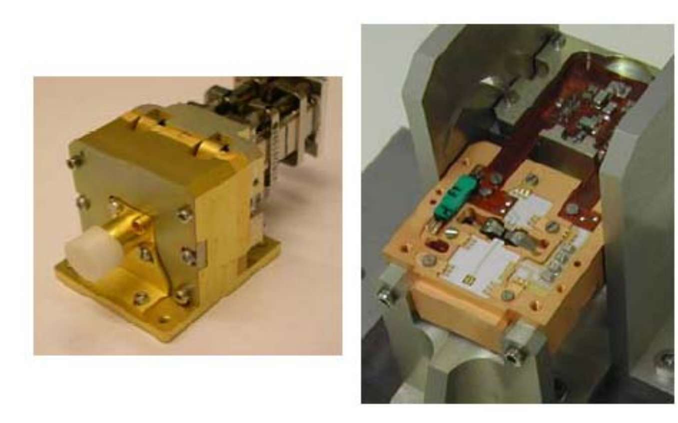

Figure 2 Band 1 mixer block’s outside and inside view

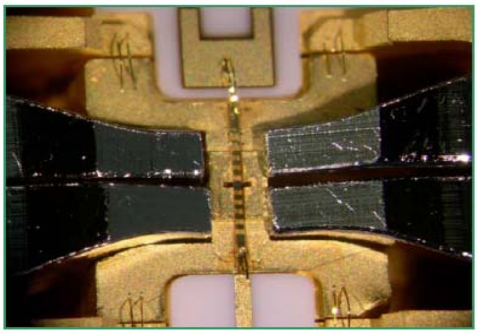

Figure 3 Detailed view of the band 1 waveguide and magnet section

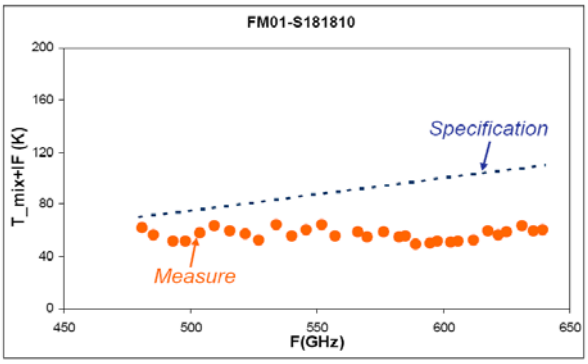

Figure 4 Noise temperature of a band 1 FM mixer unit, corrected for optics losses

IV. BAND 2

The band 2 mixers are developed by the KOSMA team [8]. The band 2 frequency range is 640-800 GHz. The superconducting gap frequency of Nb is within this frequency range and the band 2 team had to explore several electrode materials to optimize the overall performance. The final configuration is shown in Figs. 5 and 6. The design incorporates a Nb/AlOx/Nb SIS junction (Jc=15 kA/cm^2, 0.9 μm^2) with a NbTiN ground plane and a Nb top-electrode. The tuning structure is based on a single junction with a three step impedance transformer. The mechanical design of the mixer unit is shown in Fig. 7. The unit consists of several modules for the RF, IF and DC signals. These modules can be tested and optimized separately and integrated in a later stage. The horn-waveguide module is based on a design that was successfully operated at several ground based telescopes. Results of the sensitivity of the Flight Model and Flight Spare mixer units are shown in Fig. 8.

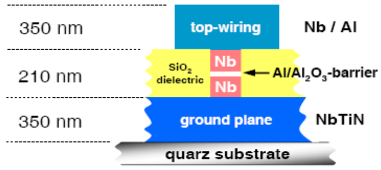

Figure 5 Device topology of the band 2 SIS mixer. The top wiring for the FM units is Nb.

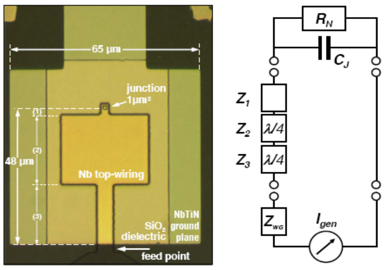

Figure 6 Left: photograph of the Band 2 junction device with the three step transformer. Right: Equivalent circuit of a three step transformer

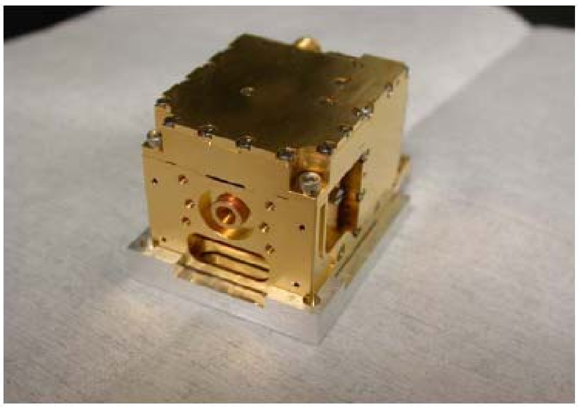

Figure 7 Band 2 mixer block

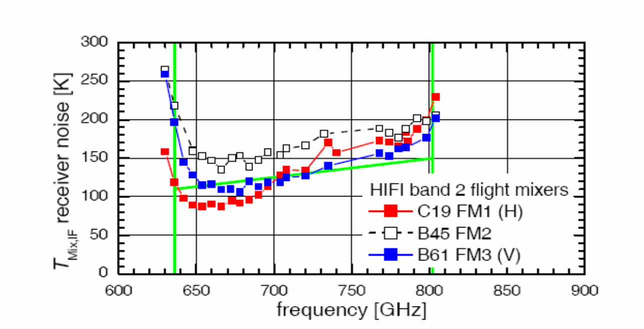

Figure 8 Noise temperature of the band 2 FM and FS mixer units (corrected for optical losses)

V. BAND 3 AND 4

Both the band 3 and 4 mixers are developed by the SRON team, in collaboration with the Kavli Institute of Nanoscience Delft, and with a contribution of JPL (band 4 NbTiN layers) [9,10]. The band 3 and 4 frequency ranges are 800-960 GHz and 960-1120 GHz, respectively. Several options for device and electrode materials have been considered and tested. Ideally one would use an SIS device with a cut-off frequency higher than the Nb-based junctions, in combination with high gap electrode materials. In practice this turned out to be a major development task in which undesired side effects were observed, like heat trapping and magnetic flux trapping instabilities. The final device and electrode configuration consists of an Nb/AlOx/Nb twin junction design (Jc=5-10 kA/cm^2, area 0.6-1 µm^2), with an NbTiN ground plane and an Al top electrode (see Fig. 9). The highest operating frequency really pushes the Nb-based junctions to the limit. Fig. 10 shows that only a limited, but still sufficient, bias range is available for operation at these high frequencies.

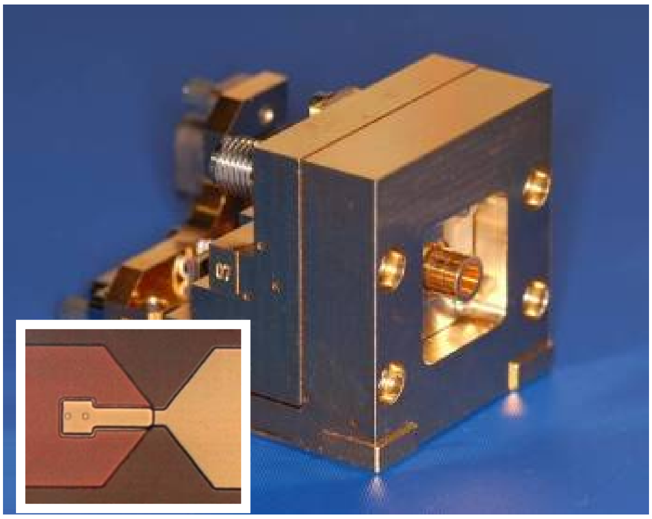

Figure 9 Band 3/4 mixer block. The inset shows the twin junction geometry with the tuning structure.

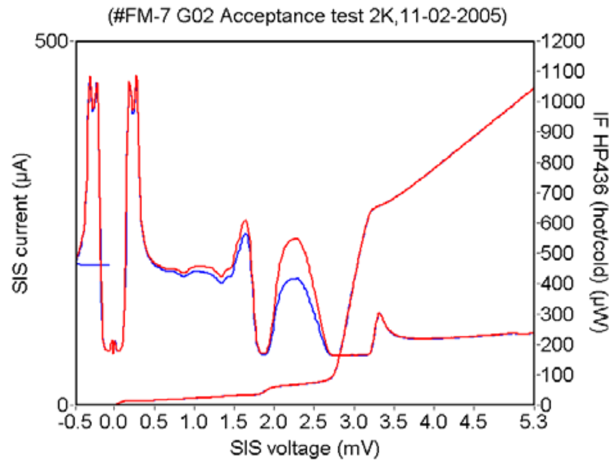

Figure 70 Pumped I-V curve and the IF output power with hot and cold input, measured at 1150 GHz. Notice the limited bias range around 2.3 mV.

Some details of the mechanical design of the band 3 and 4 mixers are shown in Figs. 9, 11, and 12. To be independent of machining tolerances, the unit incorporates an in-situ alignment of the horn with the backpiece. To facilitate a clean and reproducible device mounting, the device substrate is suspended in the substrate channel and mounted with silver epoxy on an alumina ring structure. In this way no glue has to be applied in the delicate substrate channel.

Results of the Band 3 and 4 FM units as measured by the SRON team are shown in Fig. 13. These results are corrected for the optical losses of the beam splitter and the dewar window. The results are very good. It can be seen though that with the used device technology it is difficult to fabricate mixer units with exactly the same performance, even if the device geometry on the photolitographical mask is equal. This is due to the slight variations that occur during the device fabrication process (with optical lithography) and the unavoidable tight tolerances of the tuning structure at these high frequencies.

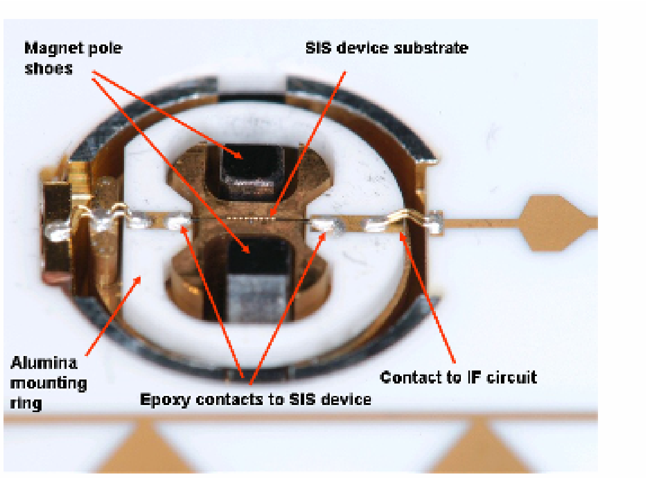

Figure 81 Details of the waveguide and substrate channel of the band 3 and 4 mixers. The SIS device substrate is mounted with two silver epoxy contacts.

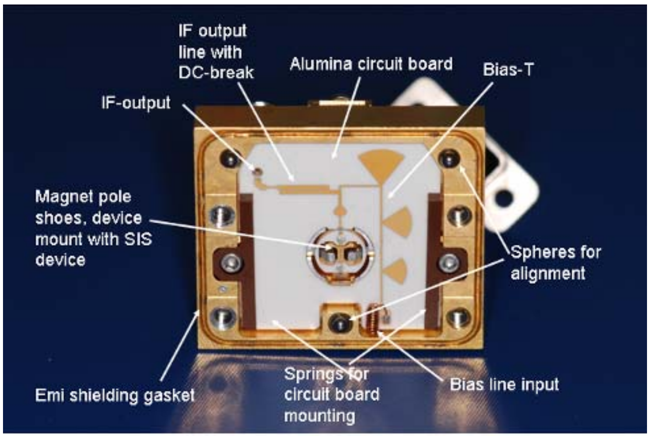

Figure 92 Inside view of the band 3/4 mixer unit. The IF board holds the bias-T and the planar DC-break.

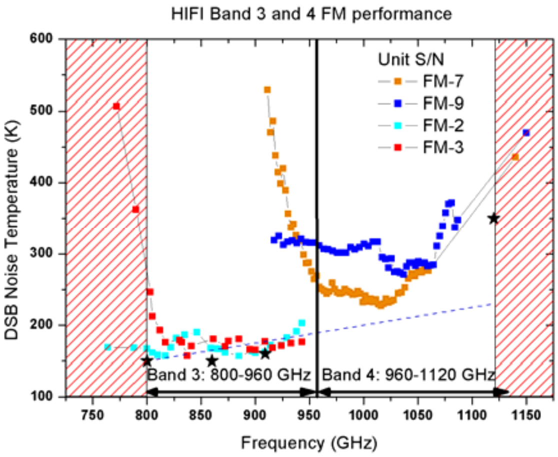

Figure 103 Noise temperature of the band 3 and 4 FM mixer units. The upper part of band 4 could only be measured at selected frequencies, due to a lack of LO power.

VI. Band 5

The Band 5 mixer units are developed by the Caltech/JPL team [11]. The band 5 frequency range is 1120-1250 GHz. The SIS devices for band 5 are high current density Nb/AlN/NbTiN junctions (30 kA/cm^2) with a gap voltage of 3.5 mV (compared to 2.8 mV for all Nb SIS devices). The area of the devices is 0.25 μm^2. The advantage of these devices is the high RF bandwidth (because of the high current density) and the lower mixer conversion loss (compared to Nb devices) at the band 5 frequency range.

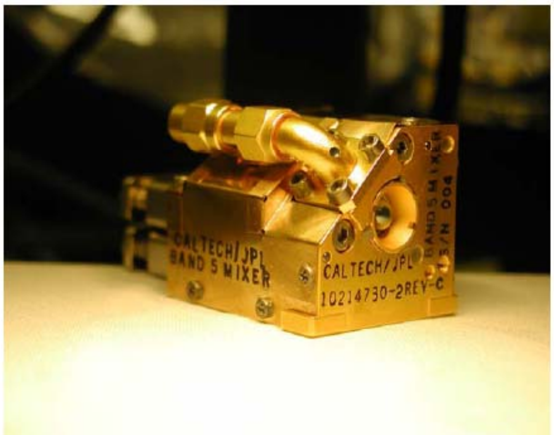

Figure 14 Band 5 mixer block

The electrode material is epitaxial Nb for the ground plane and Au for the top electrode. The quasi-optical RF coupling is established via a hyper-hemispherical Silicon lens (coated with an anti-reflection layer) and a twin slot antenna (Fig. 14). The RF tuning structure consists of a twin junction design with a virtual ground. To facilitate the suppression of unwanted Josephson effects the junctions (which are defined with e-beam lithography) have a diamond shape.

Results of a calibration measurement of band 5 are shown in Fig.15. Compared to Fig. 9 we can clearly see the advantage of the higher gap voltage. The very effective suppression of the DC -Josephson effect is shown in Fig 16. Results of the mixer sensitivity as measured by the Caltech team are shown in Fig. 17.

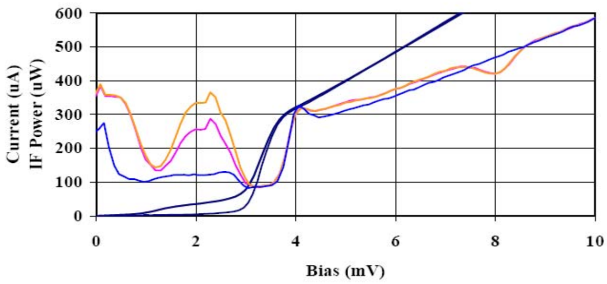

Figure 15 Pumped and unpumped I-V curve and the IF-output with hot and cold input loads at 1130 GHz.

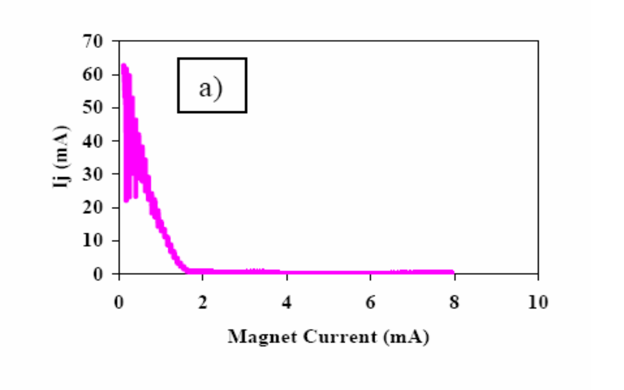

Figure 16 Zero voltage Josephson current vs the magnet current.

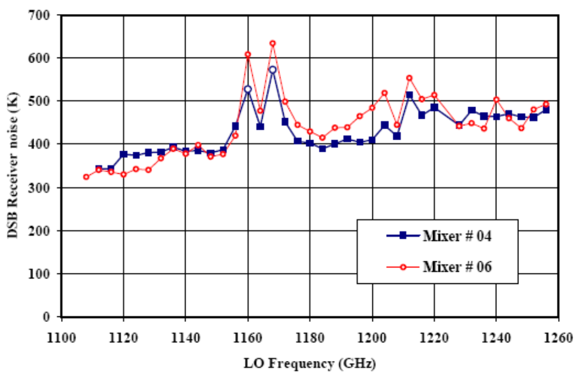

Figure 17 Measured DSB noise temperatures of the band 5 FM mixers.

VII. Band 6L and 6H

The band 6L (Low) and band 6H (High) mixers are developed by the Chalmers group, together with JPL and the Moscow State Pedagogical University [12]. The frequency ranges for band 6L and 6H are 1410-1660 GHz and 1660-1910 GHz, respectively. The device technology for the band 6 mixers is a phonon-cooled NbN Hot Electron Bolometer (HEB). The HEB is placed in the center of a double slot antenna on a silicon chip. The HEB chip is glued on the backside of a silicon elliptical lens (Figs. 18 and 19). The HEB is made out of a 2x0.1 μm^2 NbN film with a thickness of 3-5 nm. The bolometer size is a compromise between availability of LO power on the one hand, and sensitivity and stability on the other hand. The Chalmers group together with the HIFI consortium have spent great effort in optimizing the HEB mixers for space operation. A late-stage redesign of the IF matching circuit was necessary to reduce the IF-ripple that was initially observed, and several iterations on beam measurements and optical adjustments have been performed to fulfil the optical alignment specifications. Also the application of an anti-ageing layer of 200 nm Si has been of crucial importance to protect the ultra-thin HEB devices. Some typical results of the noise temperature and broadband Fourier Transform Spectrometer measurements are shown in Fig. 20. It should be noted that due to the limited availability of LO-sources for these high frequencies, the characterisation of the mixers at Chalmers only could be performed at selected frequencies available from a FIR laser. Only within the HIFI instrument the full noise temperature characterisation could be performed. As shown in Fig. 21 the noise temperature has a slope within the 2.4-4.8 GHz IF band, due to the intrinsic phonon cooling times of the NbN HEB. Averaged across the IF band the DSB mixer noise temperatures of the band 6L and 6H mixers were 1100 K and 1450 K, respectively.

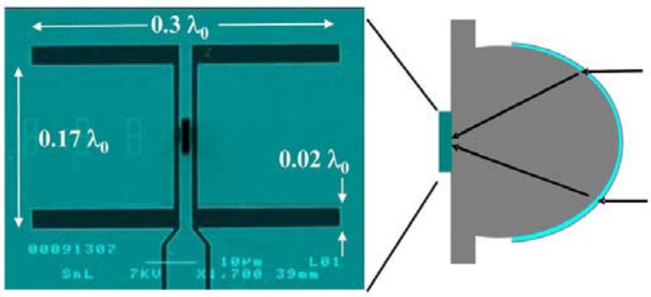

Figure 18 Left: SEM image of a double slot antenna with a HEB at the center. Right: The HEB is glued to the back of an elliptical silicon lens, covered with an anti-reflection coating.

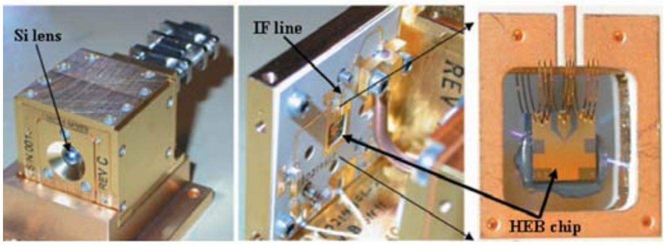

Figure 19 Left: band 6L/6H mixer unit. Middle: inside view of the mixer unit. Right: Detailed view of the HEB chip.

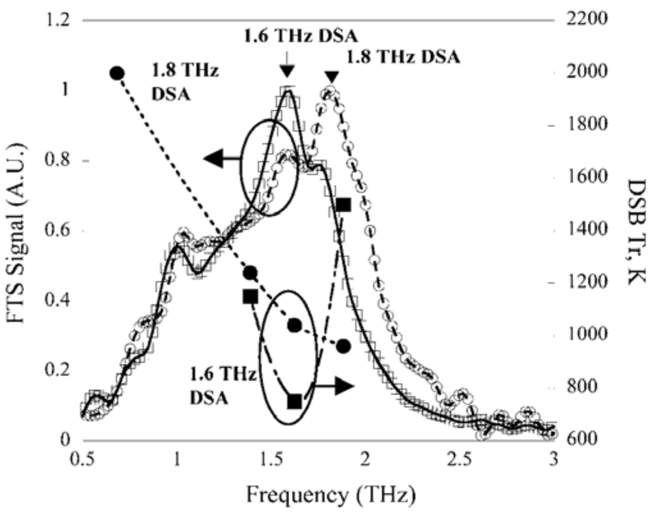

Figure 110 FTS response of 1.6 THz (band 6L) and 1.9 THz (Band 6H) mixers and the DSB mixer noise temperatures for these mixers.

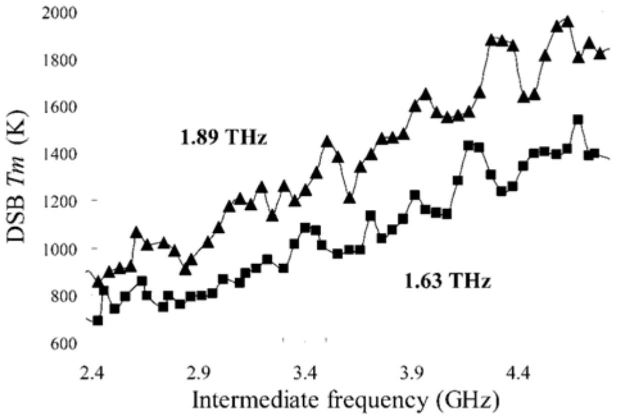

Figure 121 DSB mixer noise temperature as a function of IF frequency for the Band 6L (at 1.63 THz) and 6H (at 1.89 THz) mixer units.

VIII. Mixer Performance within HIFI

After delivery of the mixer units these were tested first at a next higher step of integration (in subunits called the Mixer Sub Assembly) and finally in the Focal Plane Unit (FPU) of HIFI. See [13]-[15] for further details on the FPU measurements. Only within the FPU the real HIFI performance can be measured. The measurements in the laboratory set-up of the mixer groups had to be corrected for losses in the optical elements that are not present within HIFI. Also assumptions had to be made on the noise contributions of the IF chain. Other characteristics that are of influence on the noise temperature calibration within HIFI are:

- The temperature of the calibration loads. Within HIFI the calibration is performed with an internal hot-cold load at temperatures of 10 K and 100 K, compared to the 80K and 300K loads that are common in a laboratory set-up. Especially for the HEB mixers this could give different calibration results, because of potential thermal effects of the hot and cold loads on the mixer bias settings (see Ref [15].)
- The LO in bands 1, 2, and 5 is coupled via a polarizing grid beam splitter, with coupling factors of 1%, 3%, and 10 %, respectively. Especially in bands 1 and 2 it was found that the balance in LO-coupling to the mixers with the orthogonal polarisations is very sensitive to fine adjustment of the polarizing grid angles. Also the LO coupling becomes very sensitive to cross-polarisation effects. The measurements with the grid beam splitter also reveiled a polarisation mismatch of the band 5 mixer. A polarisation correction had to be inserted in the optical path and this causes the noise temperature of the band 5 mixer to be higher than measured in the laboratory.
- The LO in bands 3, 4, 6L, and 6H is coupled via a Martin-Pupplet diplexer. The Martin-Pupplet diplexer will cause a parabolic noise temperature dependence within the IF band, with a 25 % increase in noise temperature at the band edges. This makes a direct comparison of the mixer laboratory measurements not straightforward. Furthermore it is found that the intricate coupling between the diplexers for both polarisations is causing some standing wave effects at the band edges. The noise temperatures for HIFI presented here are average noise temperatures over the full IF band.
- For mixer bands 4 and 6 the FPU noise temperature measurements with the HIFI Local Oscillator unit were actually the first measurements with full coverage of the RF band, due to a lack of laboratory LO sources for these frequencies.
- At some LO frequencies the output power of the LO multiplier chains is not sufficient to optimally pump the mixers. Also at some frequencies spurious signals or instabilities were observed that influenced the system noise performance [14]. Analysis shows that most of these LO frequencies can be excluded from the final observation program, without having an effect on the HIFI frequency coverage (e.g. by observing a spectral line in USB instead of LSB)

A detailed description of these effects is beyond the scope of this paper. Elsewhere in these proceedings measurements on the optical properties of HIFI (e.g. the co-alignment of the two mixers), the stability, and the Side Band Ratio (SBR) are described [13]. In Ref [13] also more details are given on the achievable system noise temperature when both polarisations are combined.

In Figure 13 we show results of the noise temperature measurements with the HIFI FPU, together with the noise temperatures as measured by the mixer groups (corrected for noise contributions of the input optics). In this figure the noise temperature in the HIFI configuration is averaged over the IF bandwidth and we display the optimum noise temperature from either the horizontal or vertical polarisation. Minimum noise temperatures within the IF band for bands 3, 4, 6L, and 6H, will even be lower than shown, because of the diplexer effect and the IF roll-off effect in band 6. The HIFI LO scan was performed with a 1 GHz grid, and rapid fluctuations in noise temperature due to LO effects at specific frequencies were removed in the plot, by taking the lowest noise temperature within a 4 GHz bin. Any remaining rapid fluctuation in noise temperature (e.g. at 640 GHz) are still caused by the behaviour of the LO. We see that the performance within HIFI is in good overall agreement with the measurements performed by the mixer groups. Some deviations are observed which are due to details of the LO coupling in HIFI (or correction of the optical losses) and the polarisation correction in band 5. The flat response of the HEB mixers in band 6L and 6H is remarkeable. The figure also shows lines indicating the status of mixer performance in 1998 (at the start of the project) and the baseline sensitivities as defined in the original HIFI proposal. The progress in sensitivity has been enormous, especially by taking into account that the status of 1998 was achieved with many narrowband mixers at some selected frequencies. The performance of the HIFI instrument is excellent and has an unprecedented sensitivity over the frequencies covered. All bands deliver state of the art performance. This performance, combined with the absence of atmospheric attenuation, will result in system noise temperatures that will never be achieved at any ground based observatory.

SUMMARY

In summary we have described the technology and performance of the mixer units that are used in the Flight Model of the HIFI instrument. An overview of the sensitivity of the mixer units as measured within the HIFI instrument is given. The overall performance is excellent and HIFI is ready to become a mission with unprecedented observing capabilities in the submillimeter frequency range.

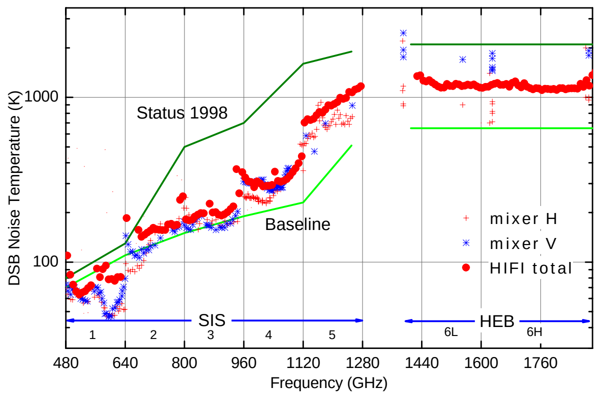

Figure 13 Noise temperature of the HIFI instrument (filled bullets) together with the results as measured by the mixer groups (for the horizontal and vertical polarisation mixers). Also shown are the sensitivity status in 1998 and the baseline performance as specified in the HIFI proposal.

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