Space-qualified SIS mixers for Herschel Space Observatory's HIFI Band 1 instrument

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Abstract **We have developed a wideband SIS mixer for the heterodyne instrument (HIFI Band 1) of ESA's Herschel Space Observatory. This double-sideband mixer uses twin Nb/AlOx/Nb junctions and, without any mechanical tuner, covers a relative bandwidth greater than 30%, optimized in the Band 1 frequency range from 480 to 640 GHz . Two identical mixers will be used in orthogonal polarizations to make up the HIFI Band 1 receiver, which, with Bands 2 to 5, will be the first SIS receivers to ever fly in space. Therefore our mixers design and fabrication process include several innovations to meet the specifications requested by a space environment, such as high operation reliability, robustness to vibration, thermal variation and cosmic irradiation. This paper presents the characteristics of the flight model and the space qualification tests performed on the qualification model. The mixer's performance analysis confirms that it has a very low noise (less than 3 times the quantum limit) over the entire bandwidth, as expected from early simulations.**

Key words: heterodyne, SIS, submillimeter, space qualification

I. INTRODUCTION

The Herschel Space Observatory is a cornerstone astronomical satellite of the European Space Agency (ESA), with a 3.5 m dish. Herschel is scheduled for launch in 2007 by an Ariane V rocket, and should operate during more than 3 years. Located at 1.5 million kilometres from the Earth (Lagrangian point L2), it will observe the universe at wavelengths so far rarely studied: far-infrared and submillimetre wavelengths for which the strong atmospheric absorption prevents ground-based observations.

HIFI is one of the three detection instruments of Herschel. It is a very high resolution spectrometer and the first space instrument using superconductive heterodyne receivers [1]. Covering a frequency range from 480GHz to 1900GHz and with a receiver sensitivity and spatial resolution higher than the previous submillimeter satellites SWAS and ODIN, HIFI will probe a large number of astrophysical sources via their rotational molecular lines.

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HIFI has 6 channels, 5 of which (band 1 to 5) use SIS technology covering continuous frequencies from 480 GHz to 1250 GHz and the last one (band 6) uses HEB technology for frequencies from 1250 GHz to 1900 GHz. Each channel contains 2 identical mixers intended to simultaneously detect two orthogonal polarizations.

LERMA has been responsible for the developement and realization of the HIFI band 1 mixers covering the frequency range from 480 to 640 GHz, in collaboration with IRAM which was in charge of the SIS (Nb/Al-AlOx/Nb) junctions' fabrication and the corrugated feedhorn's beam pattern measurements.

II. MIXER'S DEVELOPEMENT

II.1 Specifications

The key of the HIFI channel 1 receiver consists of a SIS mixer in waveguide technology, without any mechanical tuner, with a frequency bandwidth around 30% and a noise temperature near 3 times the quantum limit. In addition to the constraints imposed by the space environment, such as high operation reliability, robustness to vibration, thermal variation and cosmic irradiation, achieving both these bandwidth and sensitivity represented a technological challenge in the field of heterodyne detection.

The specifications for HIFI band 1 include:

- the noise temperature (DSB) is limited at 70K for 480 GHz and 110K for 640 GHz,
- the ripple over the whole IF 4-8GHz should be less than 2dB/GHz,
- the mixer block should weigh less than 75g and be enclosed in a volume of 32x32x40mm with all predefined connection interfaces,
- the electromagnet with a superconductor coil should be capable of suppressing the Josephson effects with a current lower than 10mA,
- the mixer block must pass the qualification tests concerning the resistance to launch vibrations, the reliability and stability in space environment.

II.2 Mixer's design

To design such device, we have developed special programs combining the theoretical physics of superconductor, of quantum mixing and of electromagnetic propagation in microstrips [2]-[5]. Using these programs and with the help of the commercial and public field simulation tools as HP-Libra, ADS, Microwave Studio, HFSS and Supermix, we have simulated the device's performance, optimized the mixer's configuration (the geometries of the feedhorn, the waveguide and the circuit's substrate)[6]-[7]. We have also predicted the effects of fabrication tolerances on the performance. A model of the mixer on 100:1 scale has been built and tested to confirm some simulation results.

The key element of this mixer, containing two SIS junctions and an integrated tuning circuit with a planar antenna, is deposited using thin film technology on a 50µm thick x 115µm wide quartz substrate. This substrate is placed in a 135µm wide channel which is orthogonal to a 100µm × 400µm reduced-height rectangular waveguide. The substrate channel and the waveguide are both closed by the same flat metal piece (Fig. 1).

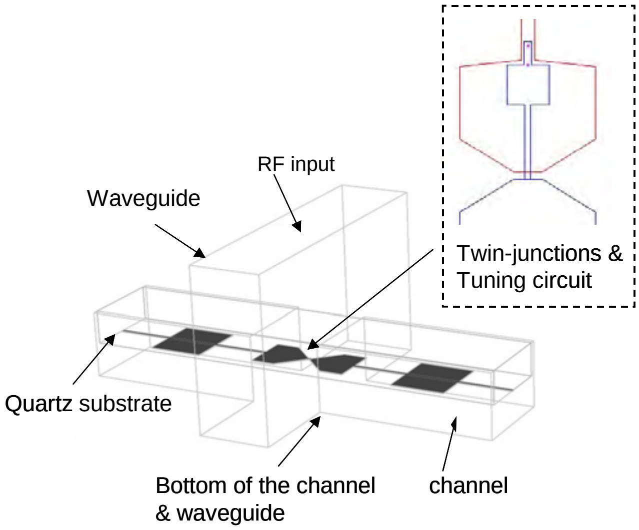


Fig. 1. mixer's configuration with no backshort waveguide and the SIS junctions' tuning circuit.

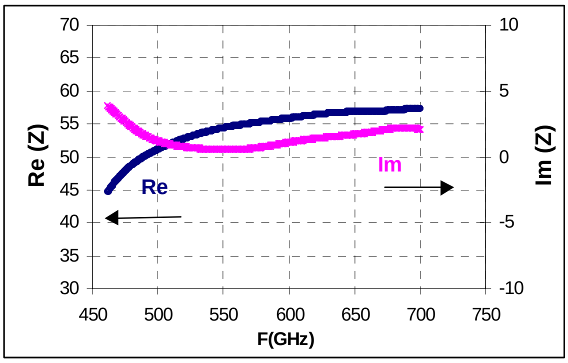


Fig. 2. embedding impedance at the bowtie antenna.

This innovative configuration has not only provided at the bowtie antenna an embedding impedance almost purely real over the whole frequency range (Fig. 2), but also allowed to skip a very critical step of waveguide alignment as in most fix-tuned waveguide SIS mixer's design. Therefore it makes the design more reliable.

The SIS junction's tuning circuit was made by using superconductive Nb stripline technology. A two-section Tchebychev transformer was designed to connect the planar bowtie antenna to twin-parallel junctions spaced by a narrow (5µm) stripline (see the box of Fig.1). The embedding impedance described above was used as an input parameter to design this matching circuit. According to the experience acquired at IRAM, the junction's area is defined as 1µm² with a current density of 10kA/cm².

During the design of the tuning circuit, the effects of parameters' uncertainties or fabrication tolerances were investigated. The circuits the least sensitive to these effects were selected .

In order to minimize the Josephson effects which cause extra noise in an SIS mixer[8], we have designed an electromagnet (Fig.3) using a high permeability cryogenic alloy "Cryoperm" (µ=30000 at 4.2 K) coiled with a superconductive wire (NbTi). This special shaped integrated electro-magnet is designed to produce, with a current lower than 10mA, enough magnetic field (about 250 Gauss in our case) to set the junction's Josephson current at the second global minimum.

Another item intended to suppress the trapped magnetic flux was designed and integrated in the mixer block : the deflux heater, a specially designed 1 kohms thin film resistor located near the junctions, able to drive them quickly from the superconducting to the normal state..

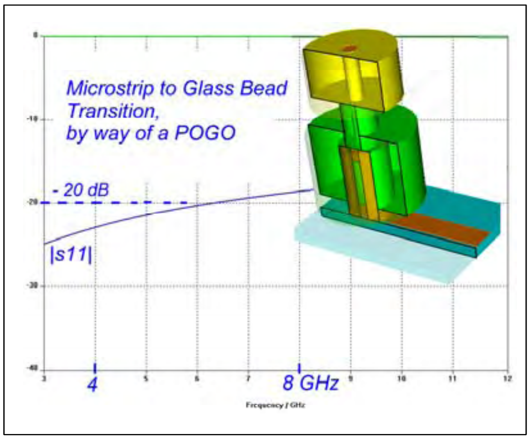


Fig. 4. spring-loaded POGO contact and the simulated S_{11} parameter for IF band.

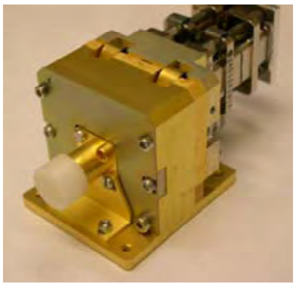
To meet the specified connection interfaces of HIFI, an orthogonal transition was needed between the mixer's IF output SMA connector and our IF board. In order to minimize this transition's return loss and have a flexible but resistant (to thermal cycles and vibrations) contact, we have chosen a SMA-pogo connector. This is a BeCu spring bellow fixed to the SMA's glass bead and pressed on the IF board via a spring allowing the right amount of pressure (Fig.4). The simulation has shown that the return loss is about -20 dB over the 4-8GHz IF band. And the qualification tests have confirmed the connector's robustness to thermal and mechanical shocks.

II.3 Mixer's fabrication

The junction was fabricated with the Nb/Al-AlOx/Nb SNEP (selective niobium etch) process using electron beam lithography, and the tuning circuits in Nb/SiO_2/Nb microstrip with the following parameters[9]: 150nm of ground-plane Nb, 200nm of SiO2, 450nm of contacting electrode Nb. The junctions have a current density between 7-9 kA/cm² and a quality factor (R_{subgap}/R_n) around 13.

The mixer blocks (containing demonstration model DM, qualification model QM and flight model FM), the high-quality corrugated mandrels and waveguides have been made by *Société Audoise de Précision* [10]. The electrodeposition and the mandrel dissolution processes have been optimized and performed in collaboration with *Protection des méteaux* [11].

This 67g mixer block's outside and inside view are illustrated in the Fig.5. It contains the corrugated feedhorn, the integrated superconductor electromagnet, the IF circuit board on alumina, the bias and filter circuits on kapton. The alumina and kapton circuit boards were fabricated by the companies *Hymec* and *Reihnart*.



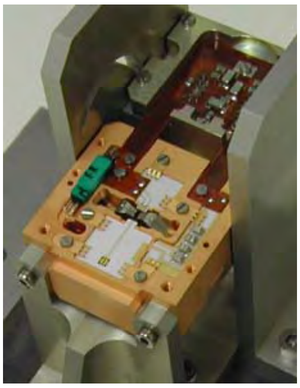


Fig. 5. Mixer block's outside and inside view.

III. MIXER'S PERFORMANCE

III.1 Space qualifications

The qualification programs are intended to submit the mixers (qualification model) to extensive tests corresponding to the constraints caused by the launch and the space environment. These programs include: thermal cycling (20-30 cycles) between 300K and 4,2K, 144 hours bake-out at 380K, vibrations at room temperature and liquid nitrogen temperature. The cold vibration tests have been performed at NLR (Holland) for each of 3 axis between 5 and 2000 Hz with a vibration level from 0,5g to 20g, levels specified by ESA and corresponding to the Ariane V rocket launch. At the end of these tests, no functional anomaly was present on the QM [12].

According to the function and the sensitivity of mixer's different elements, the specified tests determined by a pre-qualification program have been carried out separately.

Since Herschel will be exposed to cosmic radiations during more than 3 years, the effect of ionizing radiation on the junction has been studied. We performed the 10 MeV proton irradiation tests using the cyclotron at CERI-CNRS, Orléans[13]. More than 100 junctions have been irradiated with doses between 10^9 and 10^{13} protons/cm². According to the analysis, a 2.10^{10} protons/cm² dose would correspond to the 2007's launch and 4 years mission with an 1 mm thick Al shielding. After the tests, only small and not significant changes (about 1%) were observed on the junctions I-V curves.

The SIS junctions have also been submitted to the electrostatic discharge tests (performed at KOSMA, Germany). Among the 19 tested junctions, 18 junctions have resisted to 1000 pulses of 75V.

III.2 Measured performance

1. FTS measurement

The FTS measurement is performed systematically on every mounted mixer block. The mixer is mounted in an Infrared Lab liquid helium cryostat, with a 25-µm mylar vacuum window and a 180 µm zitex infrared filter.

Figure 6 shows the frequency response of the flight model FM03. The test was done under atmospheric pressure which causes the water absorption line near 557GHz. The bandwidth is larger than 480-640 GHz indicating a good performance of the RF coupling and junction's tuning circuit.

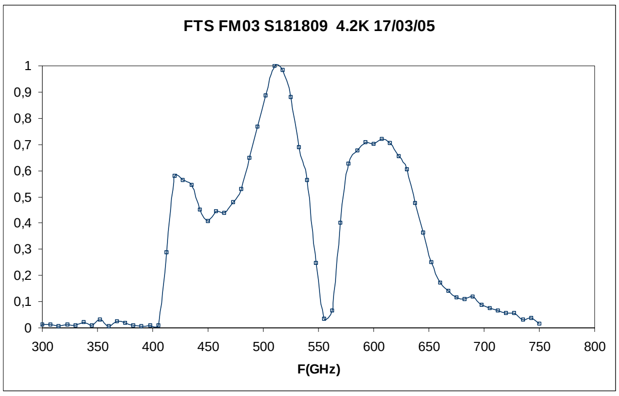


Fig. 6. FTS response of the mixer FM03.

2. *Josephson effect suppression*

The efficiency of the integrated electromagnet of the FM01 was checked and illustrated in Fig. 7. Less than 8mA coil's current was needed to produce necessary magnetic field to set the junctions to the second global minimum of Josephson current.

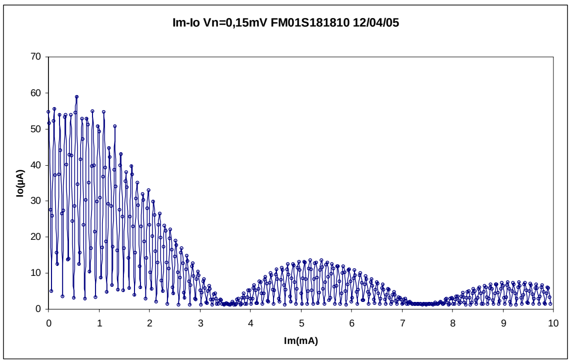


Fig.7. Josephson current of the twin-parallel junction in FM01 vs the current of the integrated electromagnet.

Figure 8 plots the two parallel junctions' IV curve of the mixer FM03 before and after applying a 14mA and 5 seconds current pulse on the integrated heater. The junctions characteristics have transited to that of a normal resistance after the pulse and returned to their initial state in about 5 seconds.

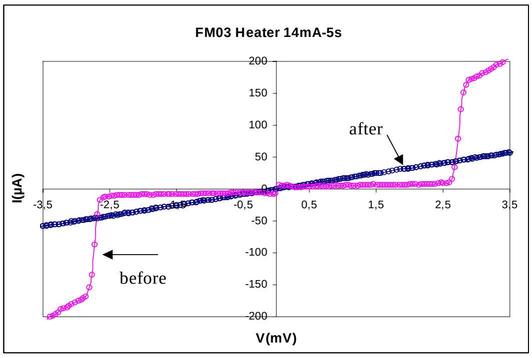


Fig. 8. Junction's IV curve of the FM03 before and after applying the 14mA and 5 seconds heating current pulse

3. *Heterodyne measurement*

Heterodyne tests were performed on two flight models for the whole band 1 frequency range using a liquid helium cryostat pumped to 2K and three RPG[14] solid state LO sources. The IF output of the mixer was connected to a 4 to 8GHz cryogenic isolator followed by a Yebes[15] low noise cryogenic HEMT amplifier with a noise temperature around 3K at a working temperature of 2K. This IF chain was calibrated using a variable thermal load at its input, as well as by the shot noise produced by the SIS junction, biased in the linear part of the IV curve above the gap voltage.

The double sideband (DSB) receiver noise temperature was obtained by the well-known "Y-factor" method, placing alternatively two blackbodies of different temperatures at the receiver input and measuring the corresponding IF output powers. From their ratio, called Y factor, one derives the receiver's noise temperature and gain. In our case, a chopping wheel switched the receiver input between a room-temperature absorber and a Thomas Keating load cooled to about 100 K, and permanently monitored in a liquid nitrogen dewar. The whole calibration setup is under vacuum, to avoid the strong attenuation of the 557 GHz water line, i.e. in the center of HIFI Band 1. The IF power was measured in the full 4-8 GHz bandwidth and in narrower bandwidths using a spectrum analyzer : Figure 9 shows the mixer's IF output power and noise temperature vs IF frequency of FM01 at 580 GHz. Across the whole 4-8 GHz IF band, the response is flat within the HIFI specifications.

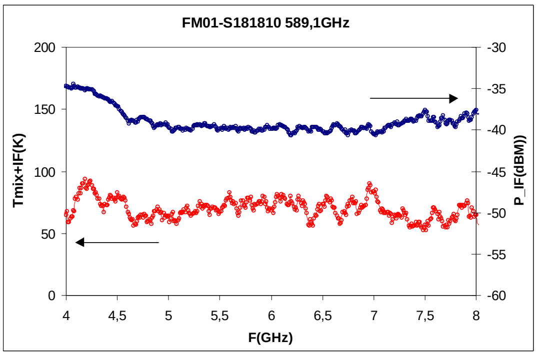


Fig. 9. IF power spectrum and receiver noise versus 4-8 GHz IF bandwidth of the FM01 at 589GHz.

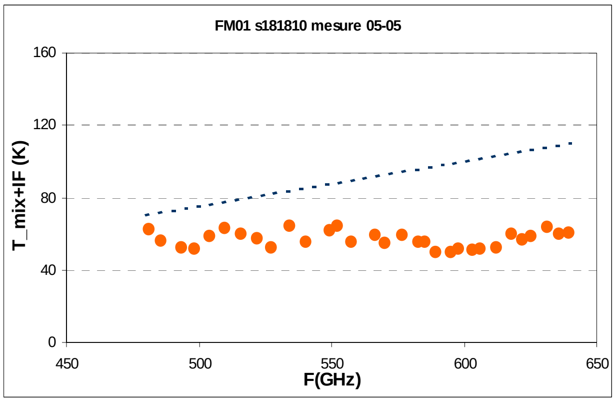


Fig. 10. Noise temperature of the mixer FM01 for the whole HIFI band 1

Figure 10 summarizes the DSB noise temperature of the mixer FM01. The noise was corrected for the optical losses, due to the various windows. These windows include those of the cryostat, of the vacuum box between the cryostat and input signal sources, and of the 10 µm mylar beamsplitter coupling the LO and load signals. The transmission of each optical component was determined experimentally by measuring its effect on the Y factor. Additional work is under way to refine this correction. We can notice that the mixer noise temperature is well under the HIFI specifications over the whole band, and therefore, smaller than three times the quantum limit. More details on the mixer behaviour (temperature vs. DC bias, LO power, magnetic field and receiver stability) will be published elsewhere.

IV. CONCLUSION

We have developed successively the demonstration, qualification and flight models of the SIS mixers for Herschel-HIFI band 1, covering the frequency range 480 to 640 GHz. These mixers include several innovative features such as a new block mechanical structure, a high-efficiency integrated electromagnet, a 4-8GHz right-angle transition using a POGO connector, and a new corrugated feedhorn process. We have fully passed the pre-qualification and qualification tests simulating the extreme conditions to which space flight hardware is subjected. The flight models have demonstrated excellent performances and satisfied all the required instrument specifications.

ACKNOWLEDGMENT

This work has been funded by the Centre National d'Etudes Spatiales (CNES) and the Centre National de Recherche Scientifique (CNRS) – Institut National des Sciences de l'Univers (INSU). We thank N. Honnigh, J. Kooi, G. De Lange, A. Kowacz, H. Golstein, P. Dieleman, J. Evers, H. Goulouze and W. Hatch for fruitful discussions, and T. De Graauw, P.J. Encrenaz, Y. Viala, G. Beaudin and J.-M. Lamarre for their supportive spirit.

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