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Development of 1.25 THz SIS mixer for Herschel Space Observatory

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ABSTRACT

We summarize the development and the delivery of two SIS mixers for the 1.1-1.25 THz band of the heterodyne spectrometer of Herschel Observatory (HSO). The quasi-optical SIS mixer has two Nb/AlN/NbTiN junctions with the area of 0.25 um^2. The Josephson critical current density in the junction is 30-50 kA/cm^2. The tuning circuit integrated with SIS junction has the base electrode of Nb and a gold wire layer.
With the new SIS mixers the test receiver maximum Y factor is 1.41. The minimum receiver uncorrected DSB noise temperature is 450 K. The SIS receiver noise corrected for the loss in the optics is 350-450 K across the 1100-1250 GHz band. The receiver has a uniform sensitivity in the full IF range of 4-8 GHz. The sub-micron sized SIS junction shape is optimized to ease the suppression of the Josephson current, and the receiver operation is stable. The measured mixer beam pattern is symmetrical and, in a good agreement with the requirements, has the f/d =4.25 at the central frequency of the operation band. The minimum DSB SIS receiver noise is close to 6 hv/k, the lowest value achieved thus far in the THz frequencies range.

Keywords: SIS mixer, THz frequency, far infrared, low noise, Herschel space observatory, radio astronomy.

1. INTRODUCTION

We developed and delivered for further integration the two SIS mixers for the 1.25 THz band of the Heterodyne Instrument for Far Infrared (HIFI) [1] of the Herschel Observatory (HSO) [2]. The goal of the HIFI project is to supply HSO with a heterodyne spectrometer with high resolution (up to 10^{6-7}), covering up to 1.910 THz to measure the C II line in the Milky Way and nearby galaxies. The HIFI should have a large instantaneous bandwidth to detect the spectral lines in the extra-galactic objects and to allow for the fast spectral surveys. The HIFI should use the state-of-the art mixers to detect faint (isotopic) lines [1].
Our contribution for the HIFI is the development of the mixers for the Band 5 of the spectrometer covering 1.12 – 1.25 THz with a mixer noise preferably in the 200-300 K range and with a broad 4-8 GHz Intermediate Frequency band. The other verifiable specifications are concerning the maximum mass of the mixer, the maximum current available for the electrical magnet, the beam width at – 11 dB and the ability to sustain the vibrations at the launch.
The SIS receiver technology is a relatively new approach to the problems of the molecular spectroscopy in a Far Infrared part of the electro magnetic spectrum. Until the development of the NbTiN based SIS devices, other technologies, as Hot Electron Bolometer or Schottky mixers, were considered as a sole competitive approach to heterodyne spectroscopy in the 1-2 THz band. Our goal is to use the Nb/AlN/NbTiN SIS junction technology advance [3] to bring in THz range the possibility to build receivers with sensitivity close to the quantum limit, already achieved with SIS mixers at the frequencies below 1 THz [4].
Below we give a short description of the mixer structure. Then we describe the test installation and the mixer performance on the delivery for integration in HIFI.

2. SIS MIXER

In this work we are using a quasi-optical SIS mixer structure, similar to one described in [5]. At the mixer chip we are using a double slot antenna with a two SIS junction array attached to the back side of a Silicon lens. For the signal mixing are used the two Nb/AlN/NbTiN junctions with the area of 0.25 μm^2 each. The Josephson critical current density in the junction is 30-50 kA/cm^2. The tuning circuit integrated with SIS junctions has the base electrode made of Nb and a gold wire layer. For more details on the mixer chip layout one can see a paper [5]. The SIS mixer general

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view is presented in Fig.1. The mixer housing with a circular hole in the middle of it front side serves to connect the Silicon lens and the mixer IF/DC board.

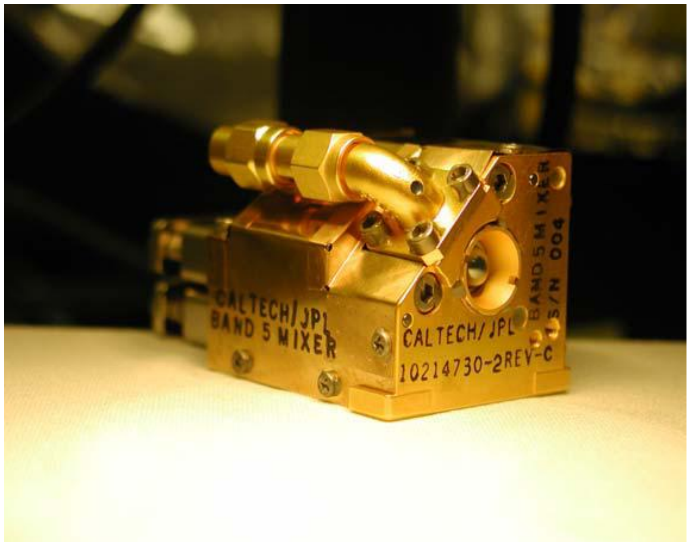


Fig. 1. A general view of the mixer delivered for integration in HIFI of the Herschel Observatory. The mixer structure is solid and sustains well the vibrations levels possible at launch.

3. TEST RECEIVER

The receiver used at Caltech for the functional test of the 1.25 THz SIS mixers consists of an Infrared Laboratories LH-3 cryostat, of the local oscillator, and of the bias electronics. The cryostat vacuum window is in Mylar 12 μm thick. An infrared filter made of Zitex is located at the 77 K stage of the cryostat. The local oscillator power is coupled to the mixer beam using a Mylar beam splitter 5 or 12 micron thick. The intermediate frequency range is 4 GHz – 8 GHz and the IF amplifier noise is about 3 K. During the test the physical temperature at the mixer block was about 2 K.

The mixer beam pattern has been measured using the heterodyne detection of a hot black body (a heater) of a small size mounted on a two-dimensional translation stage. The black body signal was modulated with a chopper and detected using a lock-in amplifier.

4. SIS MIXER PERFORMANCE IN THE TEST RECEIVER

The test receiver noise temperature was measured by Y factor method. In the measurements we used liquid nitrogen cooled and ambient temperature calibration loads. The signal from calibration load was passing about 5 cm in open air before the test cryostat vacuum window. The receiver IF power was detected in entire 4-8 GHz band. The minimum uncorrected noise measured with a 5 micrometer thick beam splitter is about 450 K (Y= 1.41). The test receiver noise corrected for the optics loss is presented in fig. 2. The performance of the two mixers is almost identical. The receiver noise versus LO frequency has a nearly linear dependence, except some residual spikes related to the effect of the laboratory atmosphere. The most visible double maximum in the receiver noise is centered at the frequency of absorption line of water at 1163 GHz, and is due to the absorption of the cold load signal in the laboratory air. The twin structure of the maximum is related to the consecutive obscuration by absorption line in the upper and lower sidebands of the test receiver. It will not be affecting the receiver when the mixer will be used in vacuum at the HSO. In more details the role of the absorption in the laboratory air is demonstrated below in Fig. 3.

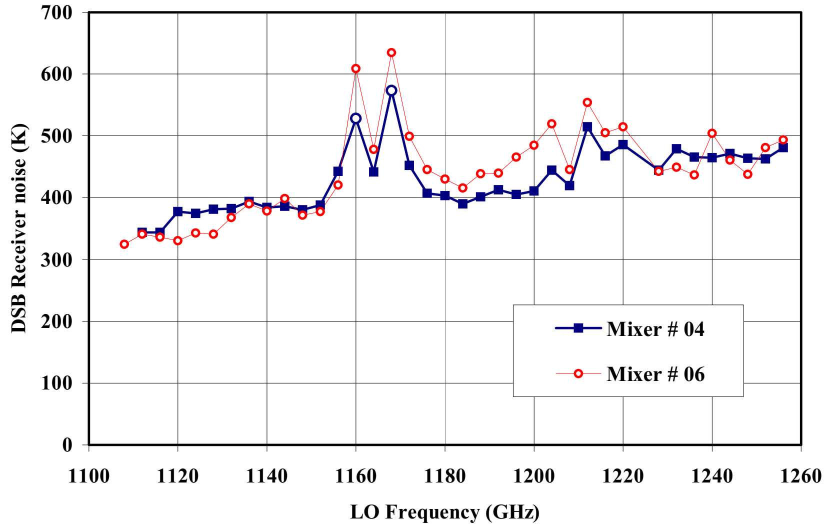


Fig. 2. Measured performance of the test receiver with the two different SIS mixers. The receiver noise is corrected for the beam splitter and for the cryostat window loss. The corrected receiver noise is below 500 K in entire 1.1 – 1.25 THz band. The minimum corrected receiver noise is 330 K, about 6 hν/k. Note a double maximum in the noise centered at the frequency of an absorption line of water vapor at 1163 GHz. Some smaller spikes in the 1.2-1.24 THz band may be also related to the absorption in the laboratory atmosphere (Fig. 3)

The estimated loss of the signal at the distance of 5 cm in the laboratory air is outlined in the Fig. 3 (dotted line). The Atmospheric Transmission at Microwave (ATM) model [6] developed by J.R. Prado *et al* was used for this calculations. When detecting with a double side band heterodyne receiver, the signal loss is averaged over the two sidebands. The solid line shows the transmission coefficient averaged over the 4-8 GHz IF side bands of a heterodyne receiver at each LO frequency. The shape and location of these minimums of transmission corresponds well to the locations of the maximums in the excess noise of the test receiver (Fig. 2).

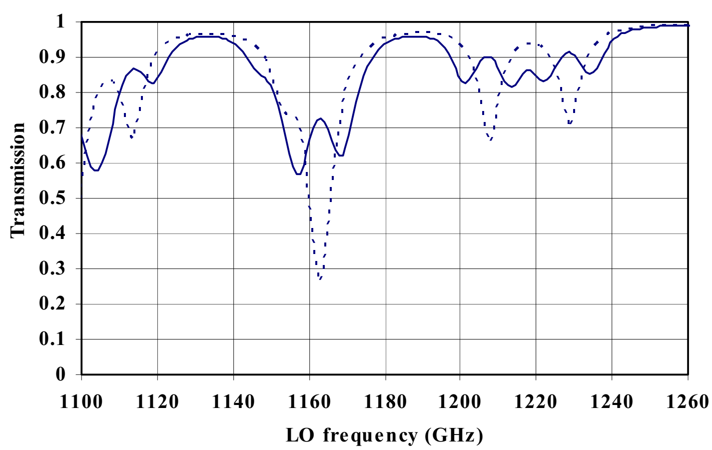
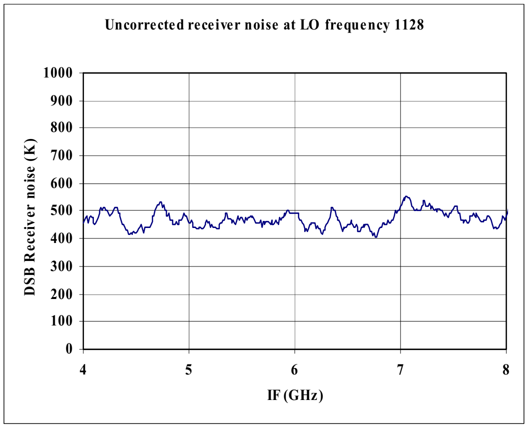


Fig. 3 Absorption in the 5 cm of the laboratory air may affect the test data. The dotted line is the transmission as a function of frequency calculated using ATM model[6] (courtesy of J.R. Prado). The solid line gives the transmission of the signal for a double side band heterodyne receiver, averaging the transmission over upper and lower sidebands

for each LO frequency. The receiver IF band is 4-8 GHz. One can mention a similarity in the shape and in location of the measured receiver noise spikes (Fig. 2) and the minimums in calculated averaged transmission (solid line).



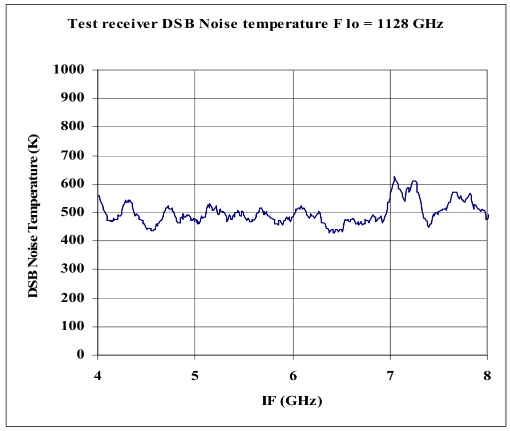


Fig. 4. The test receiver noise temperature versus Intermediate Frequency measured wit the two different SIS mixers. No corrections applied. The SIS mixer response is uniform over the entire 4 to 8 GHz IF band. Note the measured noise is below 500 K over the full IF band.

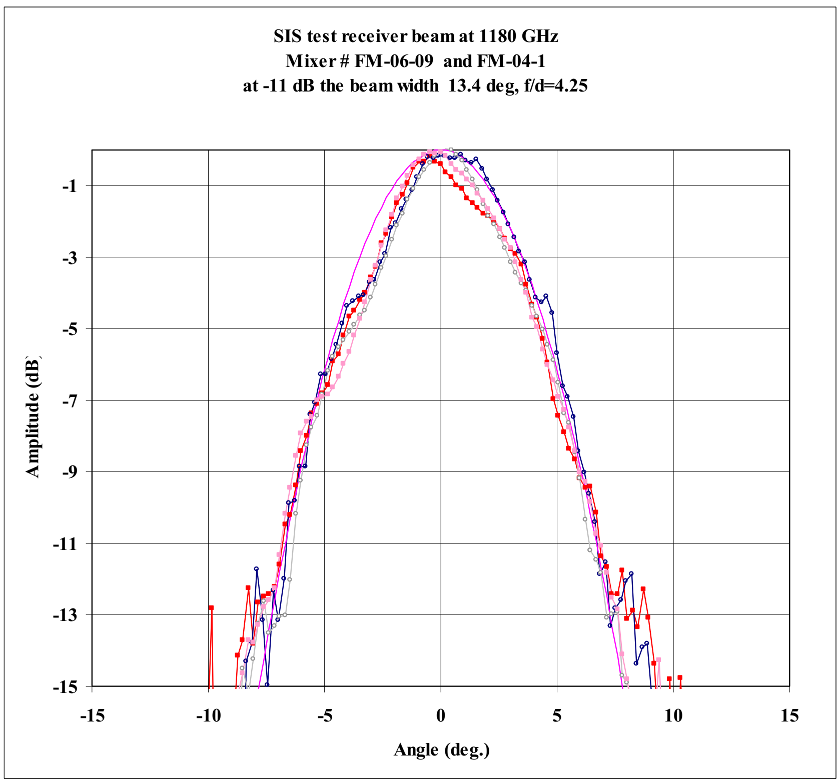


Fig. 5. The receiver beam vertical and horizontal scans measured with the two different mixers.
All the four measured beam profiles are nearly identical and fit well with the Gaussian approximation of the beam (solid line).

The uniformity of the receiver sensitivity over the full IF band has been verified using a spectrum analyzer in the Y factor measurements. The receiver noise measured at the LO frequency 1128 GHz for the two SIS mixers is presented in the fig. 4. The average receiver noise is close to the 450 K level, as mentioned before. The receiver response is uniform over the entire 4-8 GHz IF band.
The mixer beam pattern has been measured using the heterodyne detection of a hot black body (a heater) of a small size mounted at an X-Y translation stage. The black body signal was modulated with a chopper and detected using a lock-in amplifier. The beam shape was measured in vertical and horizontal planes. The data obtained for the two SIS mixer at the LO frequency of 1180 GHz are presented in the Fig. 5. All the measured beam profiles are identical within the precision of the measurements and fit well with a Gaussian approximation (solid line without dots). The measured beam is symmetrical. At the –11 dB level the beam f/d ratio is about 4.2.

5. SUMMARY

We developed and delivered two low noise SIS 1.1 – 1.25 THz band mixers for installation in a Heterodyne Instrument for Far Infrared (HIFI) at the Herschel Observatory (HSO)
On delivery mixer performance has been found to meet specifications for the use at HSO (mass, beam pattern, 4-8 GHz IF band, RF band, noise, LO power limits, Josephson current suppression).
The minimum test receiver DSB noise is 450 K (8 hν/k), the receiver noise corrected for the loss in the test cryostat optics is 330 K (6 hν/k), and the minimum mixer noise is 260 K (5 hν/k) are the lowest values achieved thus far in the THz frequencies range

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