Space-borne 640-GHz SIS Receiver Based on 4-K Mechanical Cooler

Yasunori FUJII[1], Ken'ichi KIKUCHI[1], Junji INATANI[1],
Yoshihisa IRIMAJIRI[2], Masumichi SETA[2], Satoshi OCHIAI[2],
Takeshi MANABE[2], Harunobu MASUKO[2], Takashi NOGUCHI[3],
Katsuhiro NARASAKI[4], Shoji TSUNEMATSU[4], and Toshiya SHIROTA[5]

[1]National Space Development Agency, Tsukuba, Ibaraki, 305-8505, Japan
[2]Communications Research Laboratory, Koganei, Tokyo, 184-8795, Japan
[3]Nobeyama Radio Observatory, National Astronomical Observatory,
Nobeyama, Nagano, 384-1305, Japan
[4]Sumitomo Heavy Industries, Ltd., Niihama, Ehime, 792, Japan
[5]Nihon Tsushiki Co., Ltd., Aiko-Gun, Kanagawa, 243-0303, Japan

ABSTRACT

An engineering model has been built for a space-borne 640-GHz SIS receiver. It is the key component of Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES), which is to be operated aboard the Japanese Experiment Module (JEM) of the International Space Station (ISS) in 2005. The receiver includes two Superconductor-Insulator-Superconductor (SIS) mixers cooled at 4.5 K, as well as four High-Electron-Mobility-Transistor (HEMT) amplifiers, two of which cooled at 20 K and the other two at 100 K. These components are integrated in a compact cryostat with two-stage Stirling and Joule-Thomson (J-T) refrigerators. The receiver components has been successfully cooled and the cryostat has survived random vibration tests. The 640-GHz SIS mixer, which uses a pair of Nb/AlOx/Nb junctions connected in parallel, is built so that a broad RF matching be achieved without mechanical tuners. It is followed by cooled low noise HEMT amplifiers with a noise temperature of less than 17 K. The total receiver noise temperature has been measured around 180-220 K (DSB) over the bandwidth of 5.5 GHz.

Keywords: ISS, JEM, submillimeter, SIS mixer, HEMT amplifier, 4-K mechanical cooler, low noise receiver

1. INTRODUCTION

It is desired to use SIS mixers in space for highly sensitive submillimeter observations, both for astronomical and atmospheric purposes. SMILES[1,2] on ISS/JEM was proposed and approved as a unique mission to prove this new technology in chemical researches of the stratosphere. It will make global observations of several molecules, such as ClO and HCl, which play important roles in the ozone depletion mechanism. The SMILES mission is unique not only because of SIS mixers but also because of a 4-K mechanical cooler to cool SIS mixers at 4.5 K in its mission period longer than one year. We regard the SIS mixer is indispensable to improve the sensitivity of future submillimeter observations in space, and so is the 4-K mechanical cooler to realize a long-life, compact and low-weight cooling system for the SIS mixer.

To meet scientific requirements for atmospheric researches, the SIS mixer is expected to have a broad IF bandwidth and an image-rejection capability, in addition to its characteristic low-noise performance. The broad bandwidth is required to enable simultaneous observations for numbers of important molecular species, and the image-rejection capability is important to avoid superimposition of two RF response windows. Furthermore, the SIS receiver for SMILES is to be operated with a fixed LO frequency at 638 GHz for simplicity. This has enabled us to build a receiver with no mechanical tuners.

In the following, recent progress on the SMILES receiver is described with emphases on the 640-GHz SIS mixers, broadband HEMT amplifiers, and space-qualified 4-K mechanical cooler.

2. 640-GHz SIS MIXERS

Electrical design of the 640-GHz SIS mixer for SMILES is based on the NRO 500-GHz SIS mixer[3] and CRL 650-GHz SIS mixer[4]. These mixers commonly use a Nb/AlOx/Nb device of the PCTJ (parallel-connected-twin-juncion) type[5]. Two SIS junctions are connected with a tuning microstrip-line, which enables a broad RF impedance matching without the need of any mechanical tuners in the mixer mount. Device structures are shown in Figure 1, and its dimensions are summarized in Table 1.

New aspect of the present work is its large instantaneous IF bandwidth. IF bandwidth is essential for atmospheric study, since it restricts the number of molecular emission-lines to be observed simultaneously. SMILES requires the instantaneous bandwidth as broad as several GHz and the IF frequency as high as 8–13.5 GHz. This high IF frequency will not deteriorate the SIS mixer performance, since it is still less than 2 percent of the RF frequency at 640 GHz. But we need a modified DC-bias circuit that has a broad transmission characteristic. We have developed such DC-bias circuit, and its performance is shown in Figure 2. The return loss is larger than 15 dB in the frequency range of 4-16 GHz, while the insertion loss is less than 0.6 dB. Such DC-bias circuit has been integrated in the present version of the 640-GHz SIS mixer.
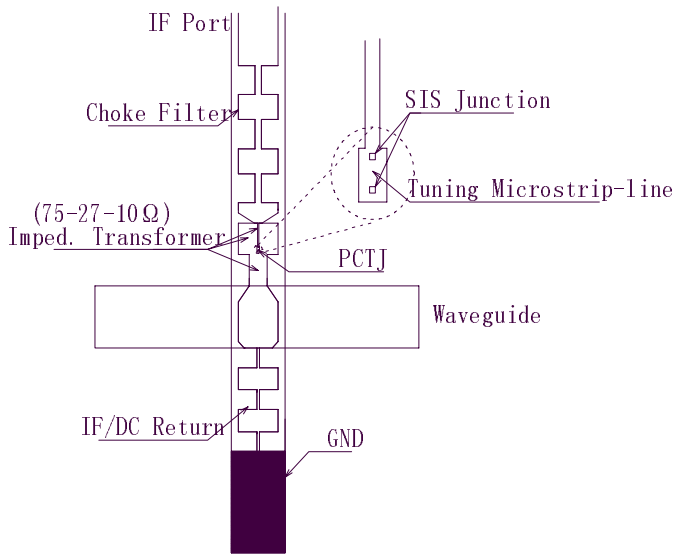
SIS device	Device size	2 mm x 0.13 mm x 0.065 mm
	SIS junction size	1.25 μm x 1.25 μm
	Current density	5.5 kA/cm^2
	Normal resistance	10.6 Ω
	$\omega R_n C_j$ at 640 GHz	8
Mixer mount	Device slot	0.14 mm x 0.14 mm
	Waveguide	0.4 mm x 0.14 mm
	Backshort	0.03 mm

Table 1. Dimensions of the 640-GHz SIS mixer device

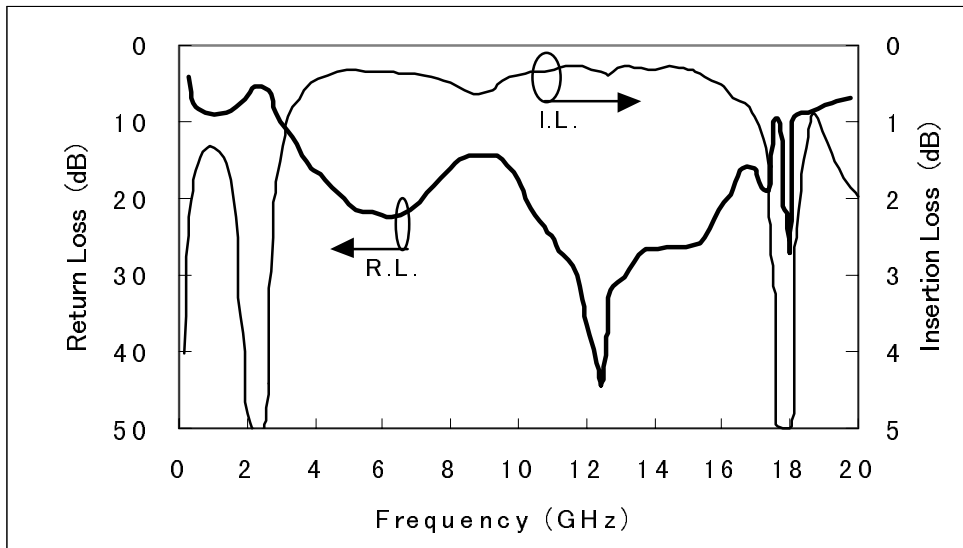Figure 1. 640-GHz SIS mixer device for SMILES

Figure 2. Measured insertion and return losses of the DC-bias circuit (Connector losses are included).

Our noise measurement apparatus for the 640-GHz SIS mixer is shown in Figure 3. We use a 4-K Gifford-McMahon (GM) refrigerator to cool an SIS mixer and two IF HEMT amplifiers. The SIS mixer is operated at 4.5 K and the HEMT amplifiers are at 4.5 K and 60 K. Large temperature ripples are often reported to occur in the 4-K GM refrigerator, synchronized with the reciprocal movement of its cold-head displacer. We have suppressed this effect to an acceptable level, as low as 30 mK (p-p), by introducing a large heat capacity of helium gas to the 4-K stage. Since the helium gas has smaller specific heat at higher temperatures, this method does not increase the cooling time[6].

The LO power, generated by the Gunn-diode oscillator and two cascaded multipliers (doubler and tripler), is injected to the SIS mixer with a beam-splitter of a 10-μm thick vinylidene chloride. Although its submillimeter reflectivity is very low, the SIS mixer has been successfully operated with a low insertion loss in this RF input section. A 500-μm poly-tetra-fluoro-ethylene (PTFE) sheet is used for vacuum sealing of the RF window of the cryostat. A 200-μm thick sheet of "Zitex" G-108, a fibrous-porous form of pure PTFE, is placed at 60-K shield to decrease the thermal radiation to 4-K stage from the RF window. The HEMT amplifiers used in this apparatus are prototype models of the IF amplifiers for SMILES receiver. They show the similar noise performance just as described in the next section.
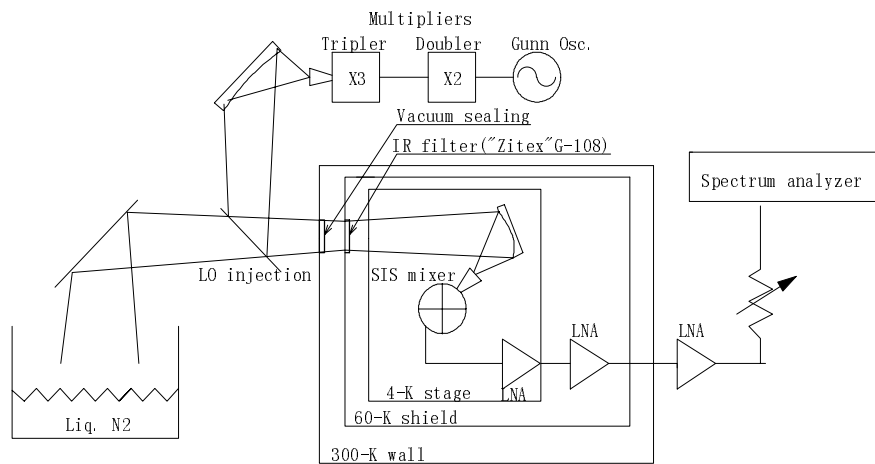

Figure 3. Noise measurement apparatus for the 640-GHz SIS mixer

Noise performance of the receiver was measured by means of the usual Y-factor method with room-temperature (295 K) and liquid-nitrogen-cooled (77 K) loads. Figure 4 shows the DSB noise temperatures of the whole receiver (T_{rx}) for the LO frequency of 642 GHz. T_{rx} of 140 - 160 K has been obtained in the IF band of 8-13.5 GHz. Although SMILES uses only one fixed LO frequency, T_{rx} was measured as a function of LO frequency to evaluate the resonance frequency of PCTJ in Figure 5. The lowest values of T_{rx} were obtained at the LO frequencies around 640 GHz, as expected from the design.
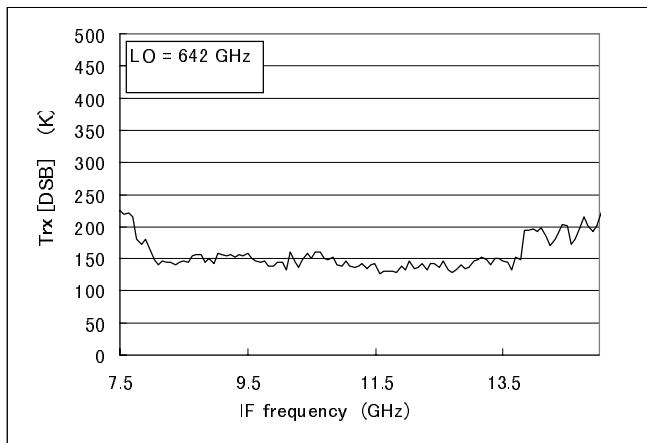

Figure 4. Measured T_{rx} of the 640-GHz SIS mixer as a function of IF frequency.
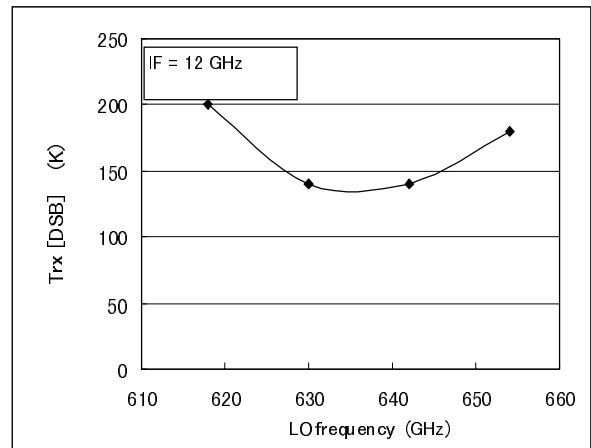

Figure 5. Measured T_{rx} of the 640-GHz SIS mixer as a function of LO frequency.

3.   LOW-NOISE HEMT AMPLIFIERS

The IF amplifiers for SMILES are required to have a broad instantaneous bandwidth. To meet this requirement, two types of broadband HEMT amplifiers have been developed: one for 20-K stage and the other for 100-K stage. The former is consisted of two HEMT devices, and the latter of three HEMT devices.

HEMT amplifiers are one of the major heat sources in the SMILES cryostat described in section 4. Therefore, a drastic reduction in heat dissipation has been an important requirement. HEMT devices are usually operated in recommended conditions such as a drain voltage of 2 V and a drain current of 10 mA. With two amplifiers at 20-K stage, we will then have a heat dissipation of 80 mW. It is beyond the reasonable conditions of the realistic cooler for space-use. However, we have found that some HEMT devices (e.g. FHX76LP) keep a low-noise performance, with a little decrease of gain, even when the drain voltage is decreased to 1 V and the drain current to 5 mA. This helps us reduce the power dissipation to 20 mW at 20-K stage, and to 30 mW at 100-K stage.

We have developed HEMT amplifiers for 9-14 GHz, and measured the performance in such starved bias conditions. The 20-K amplifier has noise temperatures less than 17 K and gains larger than 23 dB. For the 100-K amplifier they are less than 27 K and larger than 30 dB. The noise temperature of 20-K amplifier including input losses, due to an isolator and a 70 mm-long CuNi cable, should be used to evaluate the effect on T_{rx}. Such measurements are also shown Figure 6.
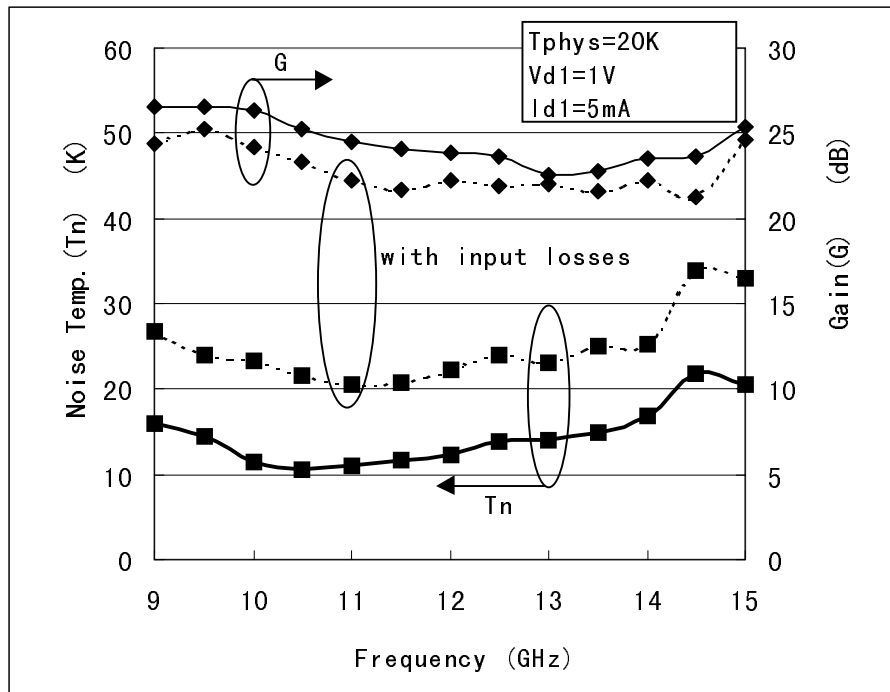

Figure 6. Measured performance of the 20-K HEMT amplifier with a heat dissipation of 10 mW. Solid lines show the performance of the 20-K amplifier alone. Dotted lines show its performance including losses due to the cable and isolator between SIS mixer and the 20-K amplifier.

4.   4-K MECHANICAL COOLER

Either 4-K GM refrigerators or GM-assisted J-T refrigerators are widely used to cool SIS mixers for the ground-use. The GM refrigerator is however not suitable for space applications, as its compressor utilizes gravity in principle. Cooling efficiency is another decisive factor for space refrigerators, since the electric power available for instruments is usually tight. From such considerations, we have selected the combination of the Stirling cycle and J-T cycle as the most practical

solution for space-use 4-K cooler. We need a two-stage Stirling cycle to pre-cool helium gas less than 23 K and to let the J-T cycle work successfully.

Next question to answer is how much cooling capacity we need to operate the SIS mixers and HEMT amplifiers. Although the SIS mixer has to be cooled to 4.5 K or less, its heat dissipation is negligibly small. So the dominant heat loads to the 4-K stage are the thermal radiation and conduction of the cryostat. On the other hand, the HEMT amplifiers contribute a large thermal dissipation at 20-K and 100-K stages. These two stages, cooled by the Stirling cycle, also suffer the heat load due to the pre-cooling of the J-T cycle gas. The current design of the thermal balance is illustrated in Table 2. It shows that the cooling capacity such as 15 mW at 4.5 K, 210 mW at 22 K, and 1050 mW at 100 K will be sufficient to maintain the cryostat.

A 40-layer MLI (multi-layer insulation) is used to decrease the thermal radiation from the 300-K walls of the cryostat. To reduce the thermal input from the RF window, we have minimized its diameter (25 mm). Such design was made possible by introducing a convergent mirror in the 4-K stage submillimeter optics. Two IR filters, made from "Zitex" G-108, are inserted in the optical path, with one attached to the 100-K shield, and the other thermally floating between 300 K and 100 K.

We have used 12 straps of glass-fiber-reinforced-plastic (S2-GFRP) to support the 100-K shield from the outer 300-K walls. The 20-K stage is supported with four GFRP pipes from the 100-K shield. The 4-K stage is supported with four carbon-fiber-reinforced-plastic (CFRP) pipes from the 20-K stage. The heat path to the cold-head of the Stirling refrigerator is given with a bunch of thin spring-like copper sheets. This mechanism isolates the user-stages from the thermal contraction of the cold-head. Figure 7 shows the structure of the cryostat, and Table 3 summarizes dimensions of the 4-K mechanical cooler.

Cooling tests have been done successfully. The J-T compressors consume the electric power of 80 W at 30 Hz, and the Stirling compressor and cold-head displacer do 110 W at 15 Hz. The ISS/JEM supplies 120 V DC to its payload. A DC to AC converter for this refrigerator is still under development, but its prototype has demonstrated a conversion efficiency of 73 percent. Therefore, the total power consumption of the cooler is estimated 260 W DC.

The whole cryostat has been successfully tested for random vibrations at the level of 15.1 Grms. Long-term running tests have been done separately for the Stirling cycle and for the J-T cycle. Both tests have shown the cooling capability lasts over one year, although the power consumption of J-T compressor increases a little at the end of the test.

Items	Types	Heat load at each stage (mW)		
		100-K stage	20-K stage	4-K stage
RF input window	radiation	150	3	2.4
Walls (with MLI)	radiation	370	19	0.1
Supporting structures	conduction	230	47	2.4
IF cables	conduction	49	22	7.9
DC bias cables	conduction	28	5	0.6
Bias current	heat source	9	3	1
Monitor cables	conduction	11	4	0.6
HEMT amplifiers	heat source	30	20	-
J-T gas cooling	heat source	170	87	-
Total load		1050	210	15
Temperature		100 K	22K	4.5 K
Refrigerator		Two-stage Stirling		J-T
Power consumption	AC	110 W (15 Hz)		80W (30 Hz)
	DC	260 W (120 V)		

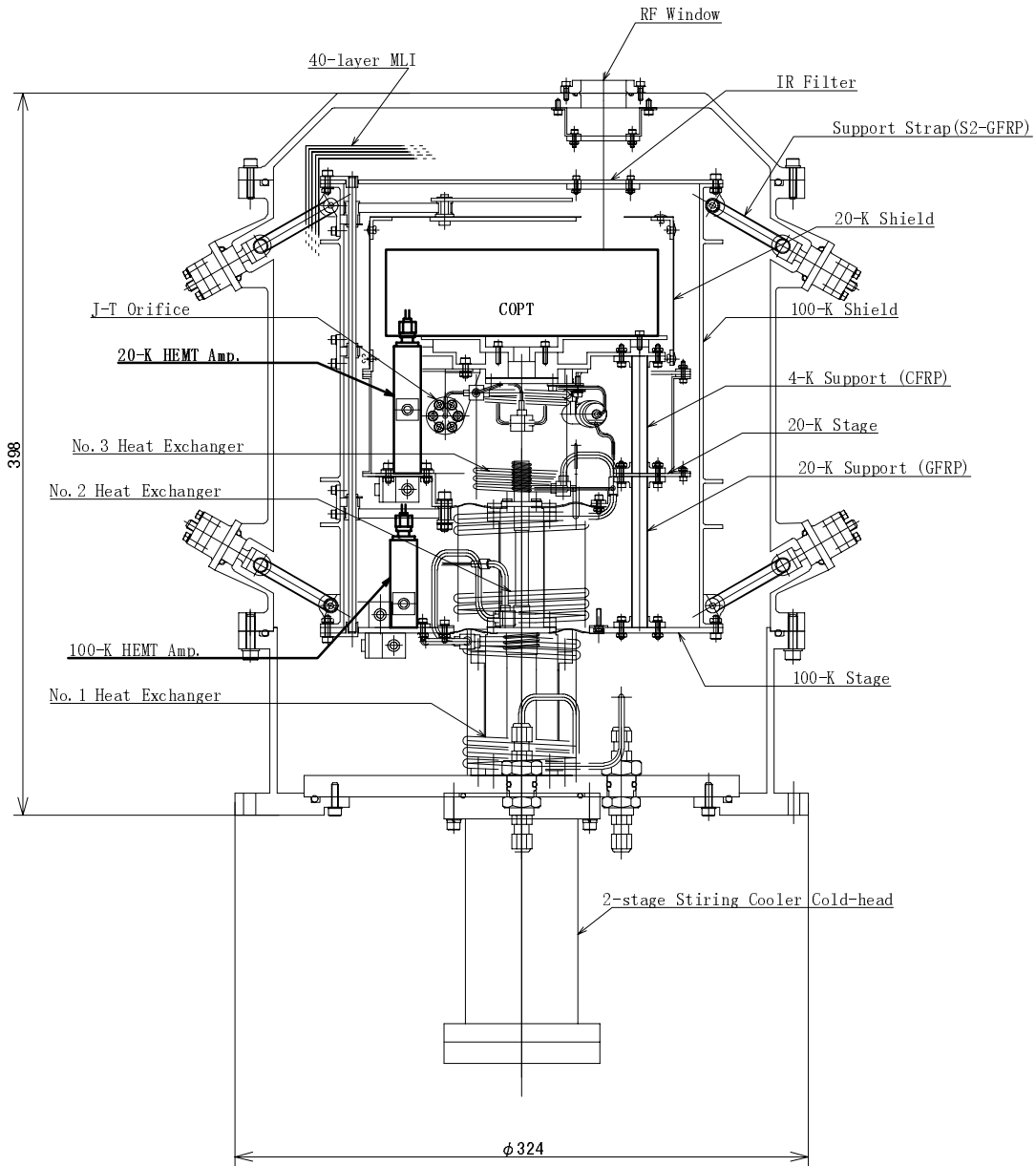Table 2. Calculated thermal balance of the 4-K mechanical cooler.

Figurer 7. Structure of the cryostat.

Items	Size (mm)	Weight (kg)
Cryostat	φ324 x 398	25
Cold-head	φ86 x 137	
J-T comp.(High)	φ80 x 360	
J-T comp.(Low)	φ80 x 360	30
Stirling comp.	φ89 x 400	

Table 3. Dimensions and weight of the 4-K mechanical cooler.

5. RECEIVER INTEGRATION

Two SIS mixers are installed in a submillimeter optical unit, COPT, at the 4-K stage of the cryostat. COPT includes three mirrors and a polarizing wire-grid as shown in Figure 8. The RF and LO signals are introduced to COPT from the top panel of the cryostat and reflected toward the wire-grid, which separates the beam into two SIS mixers. So one mixer receives a horizontally polarized beam, and the other does a vertically polarized one. Since we have a pair of frequency-selective-polarizers (FSP[7]), which is a modified version of Martin-Puplett interferometer, between the SMILES antenna and the cryostat, one SIS mixer looks at the telescope in its upper sideband (USB), and the other in its lower sideband (LSB). For both mixers, the image-band is terminated to the cold-sky background. Thus the SMILES receiver will be operated in the single sideband (SSB) mode. But descriptions are given in this paper only for the double sideband (DSB) performance that is measured for the cryostat without the pair of FPS's.
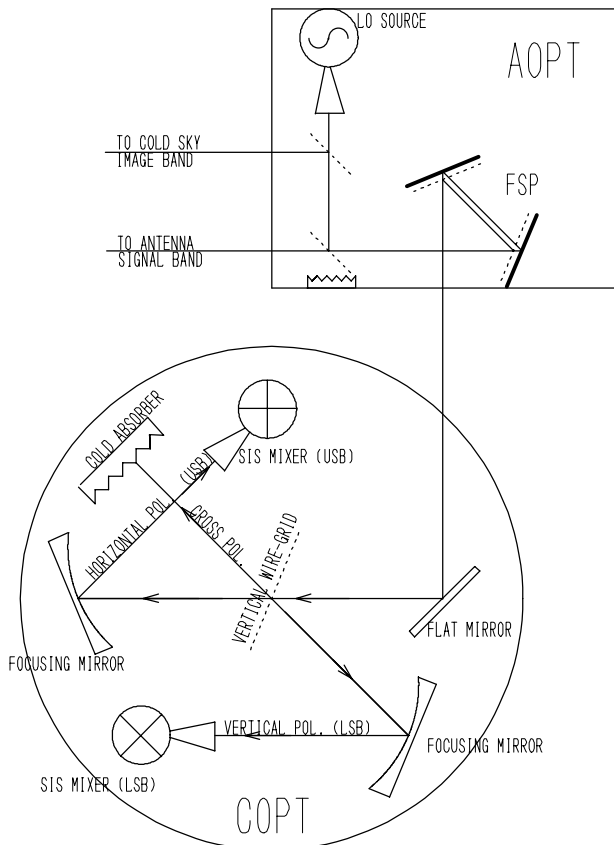

Figure 9. SMILES receiver integrated with the 4-K mechanical cooler
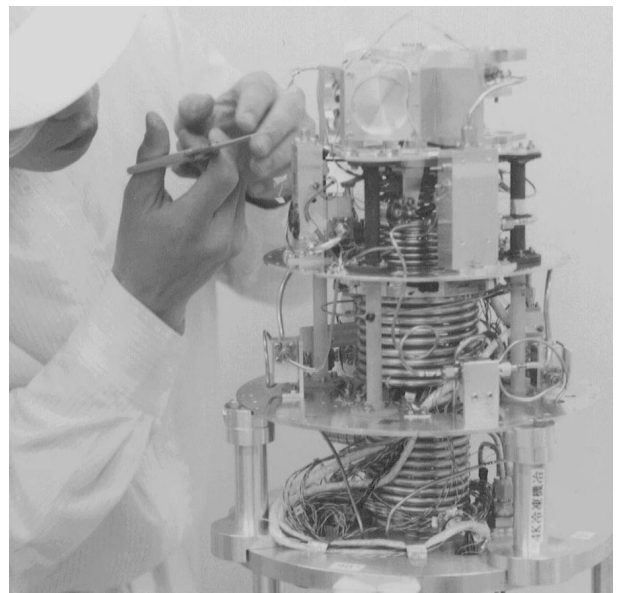
Figure 8. Submillimeter optics of the SMILES receiver.

With COPT and HEMT amplifiers assembled in the cryostat, the DSB receiver noise temperatures have been measured for the LO frequency of 638 GHz. Measured values were 180-220 K in the IF band of 8.0-13.5 GHz (Figure 10). We made a breakdown of the receiver noise temperature according to the signal flow of the SMILES receiver as shown in Figure 11. Noise contributions are separately estimated for the RF input section, SIS mixer, 20-K and 100-K amplifiers, and IF cables (including the IF isolators).

The noise temperature of the RF input section, T_{RF}, was measured by the so-called intercept method, which utilizes the small change of the mixer gain as a function of its LO power. Its measured value was around 80 K. It is attributed to the losses of

RF input section including the RF mirrors, LO injection film, vacuum window, IR filters, and SIS mixer's horn. T_{RF} is expressed as

$$T_{RF} = (1/G_{RF} - 1)T_{amb} \tag{1}$$

with G_{RF} and T_{amb} representing the gain and equivalent physical temperature of the RF input section. If we assume $T_{amb} = 290$ K, G_{RF} is derived as –1.0 dB.

In order to evaluate the noise temperature, T_{mx}, and conversion gain, G_{mx}, of the SIS mixer, we have to know the noise contribution from the IF chain. For this purpose, the receiver output power, $P_{out,}^{Vgap}$, with the SIS mixer biased at its gap voltage (2.7 mV) was regarded as attributed to the IF-chain[3]. This is expressed as

$$P_{out}^{Vgap} = T_{IF}G_{IF}k\Delta f \tag{2}$$

where T_{IF}, G_{IF}, k, and Δf denote the noise temperature, gain, Boltmann constant, and bandwidth. On the other hand, the receiver output power corresponding to the input signal temperature, T_{in}, is expressed as

$$P_{out}(T_{in}) = (T_{in} + T_{rx})G_{RF}G_{mx}G_{IF}k\Delta f \tag{3}$$

$$T_{rx} = T_{RF} + \frac{T_{mx}}{G_{RF}} + \frac{T_{IF}}{G_{RF}G_{mx}} \tag{4}$$

.
Therefore, the product of $G_{RF}G_{mx}$ is derived from the following ratio:

$$\frac{P_{out}(T_{in})}{P_{out}^{Vgap}} = \frac{T_{in} + T_{rx}}{T_{IF}}G_{RF}G_{mx} \tag{5}$$

This ratio was 7.75 dB for $T_{in} = 295$ K. If we use the measured values for T_{rx} and T_{IF}, we get the G_{mx} value of –5.0 dB. T_{mx} is then derived as 30 K from (4).

Noise contribution of each component is summarized in Table 4. The noise temperature of each component alone, T_n, is given as well as the noise contribution of each component, ΔT_{rx}, evaluated at the input port of the receiver. We see the mixer noise temperature is sufficiently low, but its conversion gain is not so high. This has increased the noise contribution of the IF-chain. High additional noise at the RF input section is probably due to the imperfect optics in this experiment. These are to be improved in the next phase of the development.
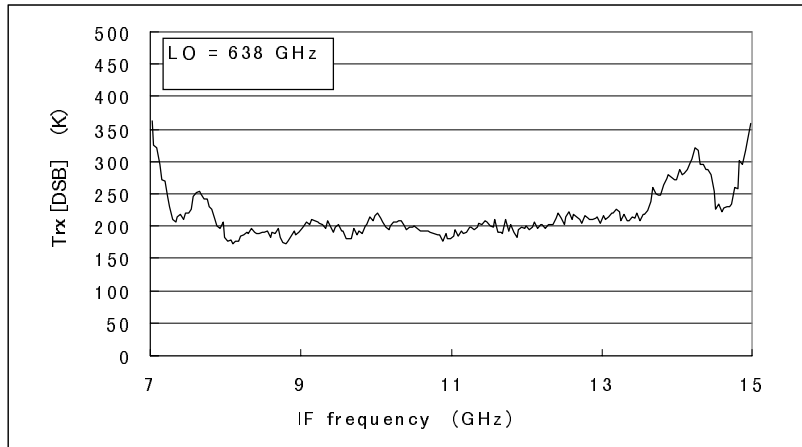

Figure 10. Measured T_{rx} of SMILES receiver as a function of IF frequency.
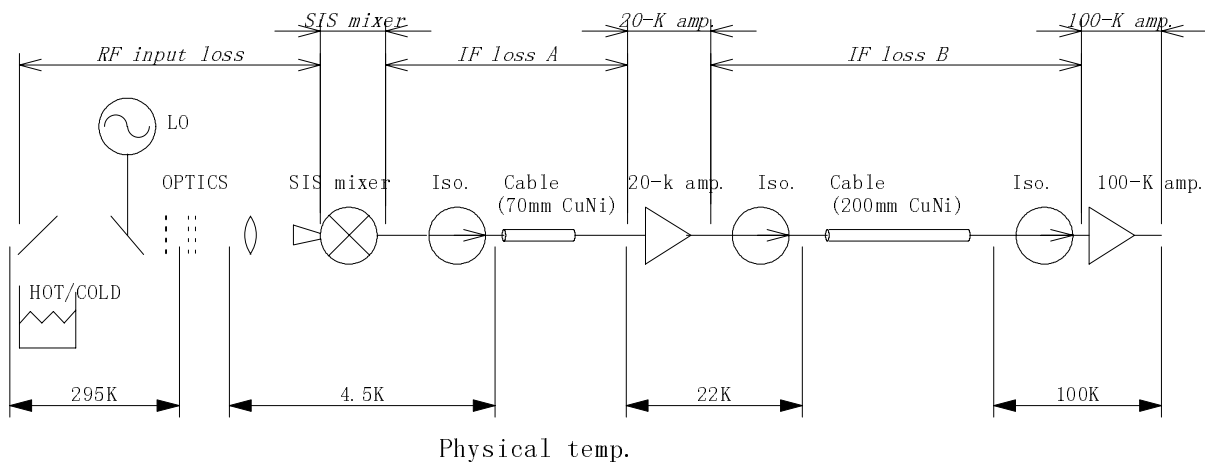
SIS mixer   20-K amp.   100-K amp.

RF input loss   IF loss A   IF loss B

LO

OPTICS   SIS mixer   Iso.   Cable   20-k amp.   Iso.   Cable   Iso.   100-K amp.
                                        (70mm CuNi)   (200mm CuNi)

HOT/COLD

295K   4.5K   22K   100K

Physical temp.

Figure 11. Signal flow in the SMILES receiver.

	RF input loss	SIS mixer	IF loss A	20-K amp.	IF loss B	100-K amp.	
Gain (dB)	-1.0	-5.0	**-1.2**	**23.9**	**-3.0**	**33.9**	
Phys. Temp. (K)	290	**4.5**	12	**22**	60	**100**	
T_n (K) [*A]	**80**	30.2	3.8	**12.3**	11.9	**20.8**	Trx (K)
ΔT_{rx} (K) [*B]	**80**	38.5	15.1	65.3	0.2	0.9	200.0

Table 4. Noise breakdown. **Bold figures** are measured values. Hatched figures are assumed values. Other figures are calculated values.
Note : [*A] Noise temperature of each component.
[*B] Noise contribution of each component evaluated at the input port of the reciever..

6.   CONCLUSION

A prototype of 640-GHz SIS mixers and low-noise HEMT amplifiers has been built for SMILES. The noise temperature of the 640-GHz SIS mixer alone was estimated as 30.2 K (DSB). A two-stage HEMT amplifier, operated at 20 K, has shown noise temperatures less than 17 K and gains larger than 23 dB with a heat dissipation of 10 mW. On the other hand, a three-stage HEMT amplifier, operated at 100 K, has shown noise temperatures less than 27 K and gains larger than 30 dB with a heat dissipation of 15 mW. Both types of amplifiers have a broad instantaneous bandwidth for 9-14 GHz.

An engineering model of the 4-K mechanical cooler, which is dedicated for the SMILES receiver, has been built. The absolute cooling capacities of the refrigerator were evaluated as larger than 15 mW at 4.5 K, 210 mW at 22 K, and 1050 mW at 100 K. These capacities were obtained with the AC power of 190 W, supplied to three helium compressors and one cold-head motor. With a high conversion efficiency, 73 percent, obtained in a prototype of DC to AC converter, we expect this 4-K mechanical cooler works well in space with a power consumption of less than 260 W DC.

The SIS mixers, HEMT amplifiers and 4-K refrigerator have been integrated in the cryostat. This was successfully cooled. It has proved an instantaneous IF bandwidth as broad as 5.5 GHz, while keeping its receiver noise temperatures around 200 K

(DSB) for the LO frequency of 638 GHz. Although this is a preliminary result, it encourages us to move on to the next step of the development.

ACKNOWLEDGMENTS

REFERENCES

1. T.Manabe *et al.*, "Space-Station Borne Submillimeter-Wave Limb-Emission Sounder for Observing Stratospheric Minor Constituents," *URSI Commission F Int. Triennial Open Symp.Wave Propagation and Remote Sensing*, September, Aveiro, 1998
2. H.Masuko *et al.*, "Demonstration of Superconducting Submillimeter-wave Limb Emission Sounder (SMILES) for observing Trace Gases in the Middle Atmosphere Using The Exposed Facility of the Japanese Experimental Module (JEM) of the International Space Station," *Space Technology and Applications international Forum,* 1999.
3. S.C. Shi, T.Noguchi, and J.Inatani, "Development of a 500-GHz Band SIS mixer," *IEEE Trans. Appl. Supercond.*, vol.7, no.2, pp.2587-2590, June 1997.
4. Y.Irimajiri, T.Manabe, S.Ochiai, H.Masuko, T.Noguchi, and S.C.Shi, "A 650-GHz band SIS Receiver for Balloon-borne Limb-Emission Sounder," *IEEE Seventh Int. Conf. on Terahertz Electro*. PP.222-224, Nara, November, 1999
5. T.Noguchi, S.C.Shi, and J.Inatani, " An SIS mixer using two junctions connected in parallel," *IEEE Trans. Applied Superconductivity,* vol.5, no.2, pp.2228-2231, June 1995.
6. R. Li, A. Onish, T. Satoh, and Y. Kanazawa, "Temperature Stabilization on Cold Stage of 4KGM Cryocooler," *9th International Cryocooler Conf.* , New Hampshire, June, 1996
7. J. Inatani, S. Ochiai, T. Manabe, M.Seta, R.Wylde ,and D.H.Martin, "A New Configuration of the Martin-Puplett Interferometer with Low-Reflection," *IEEE Seventh Int. Conf. on Terahertz Electro*. pp.260-263, Nara, November, 1999
8. Q.Ke and M.J.Feldman,"A Technique for Noise Measurements of SIS Receiver, " *IEEE Trans. Microwave Theory Tech.,* vol.42, no.4, pp.752-755, April 1994.