A SUBMILLIMETER SIS RECEIVER COOLED BY A COMPACT STIRLING-JT REFRIGERATOR

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Abstract

We have built a prototype SIS receiver for submillimeter observations in space, which is based on a compact Joule-Thomson cooler combined with a two-stage Stirling refrigerator. Cooling capacity, 30 mW at 4.5 K, 200 mW at 20 K, and roughly 3 W at 100 K, has been achieved with the electric power consumption less than 260 W. A 500 GHz SIS mixer and two HEMT amplifiers are well cooled.

Introduction

It is desirable to use the SIS mixer in space, as well as on the ground, for highly sensitive astronomical or global atmospheric observations at millimeter and submillimeter wavelengths. However, the SIS mixer has to be cooled to 4 K, either with liquid helium or by a mechanical refrigerator. Although there are several trade-offs between these two cooling methods, a refrigerator is getting to be preferable for a long life mission. A single-stage Stirling refrigerator has already established its reliability in space, and a two-stage Stirling is also getting such quality. On the other hand, for the purpose of cooling to 4 K in space, the Joule-Thomson cooler seems to be the only practical solution today among several mechanical coolers. But technical reports of its experimental investigations are not so many. We designed and built a thermal prototype of a 500 GHz SIS mixer receiver, intended for the future space applications, which was cooled by a J-T cooler combined with a two-stage Stirling refrigerator.

4 K Joule-Thomson Cooler

We built a small J-T cooler which has a nominal cooling capacity of 30 mW at 4.5 K. Its major components are a helium gas compressor, J-T valve, 4 K stage, and five heat exchangers (HEX-1 to HEX-5). Schematic structure of the whole refrigerator is shown in Fig.1. HEX-4 and HEX-5 are precooled to 100 K and 20 K by a two-stage Stirling refrigerator. For the J-T compressor, we used two units of the Stirling-type compressors which are connected in series to achieve the compression ratio of about 16. Additional valves are operated to get a one-way flow of helium gas. For making the J-T effect, we used a small needle valve, whose conductance is controlled manually by means of a gas pressure actuator. For heat exchangers HEX-1, -2, and -3, concentric CuNi tubes are adopted with optimized dimensions.

Nominal cooling capacity of the two-stage Stirling is 200 mW at 20 K, and 1W at 80 K at the same time. But this first stage has the ability to cool 1.5 W at 100 K. Details of the two-stage Stirling refrigerator are described in Kyoya et al.(1994).

The present experiment was designed to operate three channel SIS mixer receiver. In this case, heat load at 100 K is very critical, as shown in the following. So we added a single-stage Stirling, which has a capacity of 1 W at 80 K, to assist the first stage cooling. However, this could be removed in the smaller version of the receiver (one or two channel receiver).

Receiver Cryostat

We built a receiver cryostat based on the above mentioned combined refrigerator. The goal of the present experiment was to demonstrate a submillimeter SIS mixer successfully operating with a small refrigerator which could be used in space. So we concentrate on the thermal performance of the refrigerator and the cryostat. Mechanical supporting structures in the cryostat are not yet well designed to survive the shock and vibration expected in launching phase. Calculated thermal balance of this cryostat is shown in Table 1.

It characterizes this type of cryostat that the heat load to the 4 K stage is small. Heat dissipation of the SIS mixer is negligible. Major heat loads are a radiation leaking through an IR filter and the IF cable connected to the HEMT amplifier. Total load to the 4 K stage is estimated about 14 mW. But the present version of the J-T cooler was designed to have a capacity of 30 mW for safety. So we have a large margin in the 4 K cooling capacity.

On the other hand, heat loads to the 20 K stage and the 100 K stage are very large. Major heat loads to the 20 K stage are the heat dissipation of the IF amplifiers and the precooling of helium gas for the J-T cycle. We used a HEMT amplifier at 2.0 - 2.5 GHz, which is composed of two transistors with a total gain of 27 dB. The HEMT device is usually recommended to be biased with a nominal condition such as a drain voltage of 2 V and a drain current of 10 mA. If this were inevitable, we would have to deal with 20 mW dissipation for each transistor. But actually we found that some HEMT devices keep a good noise temperature, with a little decrease of gain, even when the drain voltage is decreased to 1 V and the drain current to 5 mA. Although this behavior is not common to any model of HEMT devices, it is the case for some devices (e.g. MGF4318D). In Table 1, the the power dissipation of 10 mW is assumed for each HEMT device.

Major heat load to the 100 K stage is thermal radiation from the 300 K wall of the cryostat and from the RF input window (25 mm in diameter). A 40-layer MLI (multi-layer-insulation) is put between the 300 K wall and the 100 K radiation shield. In order to reduce thermal input from the RF window, an optical path with a wire-grid is used such as in Fig.3. This is to reduce the IR coupling to the 100 K shield by means of separating the submillimeter path (which looks at the IR filter) from the IR path (which looks at metal surface with low emissivity).

Helium gas precooling for the J-T cycle generates the heat load of 100-120 mW at 20 K and 180-255 mW at 100 K. These values correspond to the 4 K cooling capacity of 30 mW. They could be reduced when the 4 K capacity is reduced.

500 GHz SIS Mixer

We put a waveguide-type 500 GHz SIS mixer on the 4 K stage, together with two superconducting magnetic coils and an ellipsoidal mirror. The mixer uses a pair of Nb/AlOx/Nb junctions connected in parallel (PCTJ, Noguchi et al.(1996)), whose resonance frequency is designed at 480 GHz. Schematic drawing of the mixer is given in Fig.4. Details of the SIS mixer are described in Shi et al.(1996). Diagonal feed horn is used for simplicity. A high permeability metal is used for the magnet core to increase the magnetic field at the junction. Actually the current of several 10 mA was sufficient to suppress the Shapiro steps.

Experimental Results

Although three channel receiver was assumed in Table 1, the SIS mixer and the HEMT amplifiers were actually installed only for one channel in the experiment. Only one RF window was open, and only two HEMT amplifiers were dissipating heat including 20 K and 80 K stages. But structures, wires, and IF cables were actually the same as calculated in Table 1. So the actual heat load in the experiment is estimated to be smaller by 410 mW at the first stage, by 50 mW at the second stage, and by 4 mW at the third stage, respectively, from each value in Table 1.

It took about 70 hours to cool the mixer from room temperature to 4.3 K. In the final steady state where the SIS mixer and the HEMT amplifiers are successfully in operation, the balanced temperatures were 106 K at the first stage, 23 K at the second stage, and 4.3 K at the third stage. Helium gas flow-rate in the J-T cycle was 1.3 NL/M (normal-liter per minute). Helium gas pressures were 14.9 kg/cm^{2}A before the J-T valve, and 1.1 kg/cm^{2}A behind it. With this condition the J-T compressor consumes the electric power of 79 W at 35 Hz, and the Stirling compressor does 115 W at 15 Hz for the two-stage cold head and 60 W at 50 Hz for the single-stage cold head. So the total power consumption was 254 W at the AC power source to drive the compressors.

Noise performance of the receiver was measured by means of the usual Y-factor method between 300 K and 77 K loads. LO, at 470-480 GHz, was generated by a Gunn diode oscillator and two cascaded multipliers (x2x3) , and was injected to the mixer through a 75 μm thick Mylar film (its calculated reflectivity is 7.5 %). Measured Y-factor for the whole system was roughly 1 dB, though the same mixer shows the Y-factor of 2.4 dB (Tsys= 220 K) in the other cryostat which has a simpler RF input optics. The present worse performance seems to be attributable to imperfect optical alignment and to the residual effect of the Shapiro steps. The latter remains in the present experiment, not because of insufficient magnetic field but probably due to magnetic flux trapped in the mixer.

Conclusion

We have built a 500 GHz SIS receiver cooled by the Joule-Thomson cooler which is assisted by the two-stage and single-stage Stirling refrigerators. The whole cooling system worked well as designed, and the SIS mixer and the HEMT amplifiers were good in operation. The cooler power consumption was 254 W. It could be largely reduced by removing the single-stage Stirling refrigerator, and by optimizing the J-T compressor to 15 mW capacity at 4.5 K.

Acknowledgements

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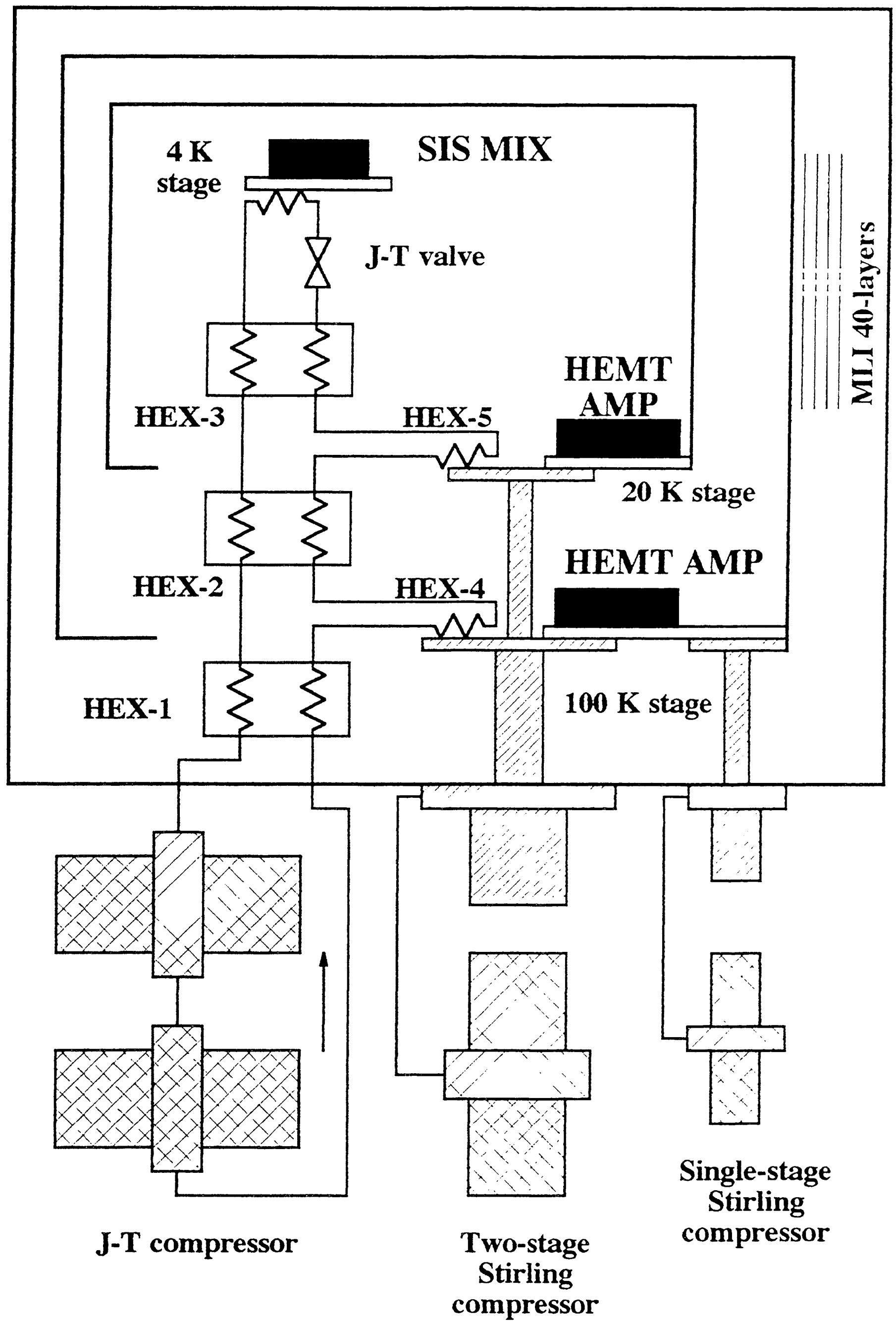

Fig. 1 A small Joule-Thomson cooler which is combined with two Stirling refrigerators: one is two-stage cycle and the other is single-stage cycle. Cooling capacity of 30 mW at 4.5 K is obtained with total power consumption of 254 W.

Items	Types	Heat Load at Each Stage			Assumptions
		1st Stage	2nd Stage	3rd Stage	
		mW	mW	mW	
RF Input Window	rad.	537	9	6	3 windows (25 mm dia. each)
Wall(area with MLI)	rad.	620	26	0	MLI 40-layers
Wall(area without MLI)	rad.	1396			
Supporting Pipes	cond.	218	16	4	3 GFRP pipes at each stage
IF Coaxial Cables	cond.	23	8	2	3 CuNi coax. cables
DC Bias Wires	cond.	9	1	0	18 Manganin wires (0.1 mm)
DC Bias Current	heat source	21	11	0	10 mA each
SCM Coil	cond.	28	7	1	6 Manganin wires (0.5 mm)
SCM Current	heat source	1	0	0	10 mA each
Temp. Monitors/Heaters	cond.	54	14	1	30 wires
HEMT AMP (1st stage)	heat source	60			3 amplifiers (6 HEMTs)
HEMT AMP (2nd stage)	heat source		60		3 amplifiers (6 HEMTs)
SIS MIX (3rd stage)	heat source			0	
J-T Gas Precooling	heat source	255	120		for 30 mW at 4.3 K
Total Load at Each Stage (mW)		3222	272	14	
Equilibrium Temperatures (K)		109 K	24 K	4.5 K	

Table 1 Calculated thermal balance of a 500 GHz SIS mixer receiver, which has three SIS mixers at the 4.5 K stage, three HEMT amplifiers at the 20 K stage, and another three HEMT amplifiers at the 100 K stage.

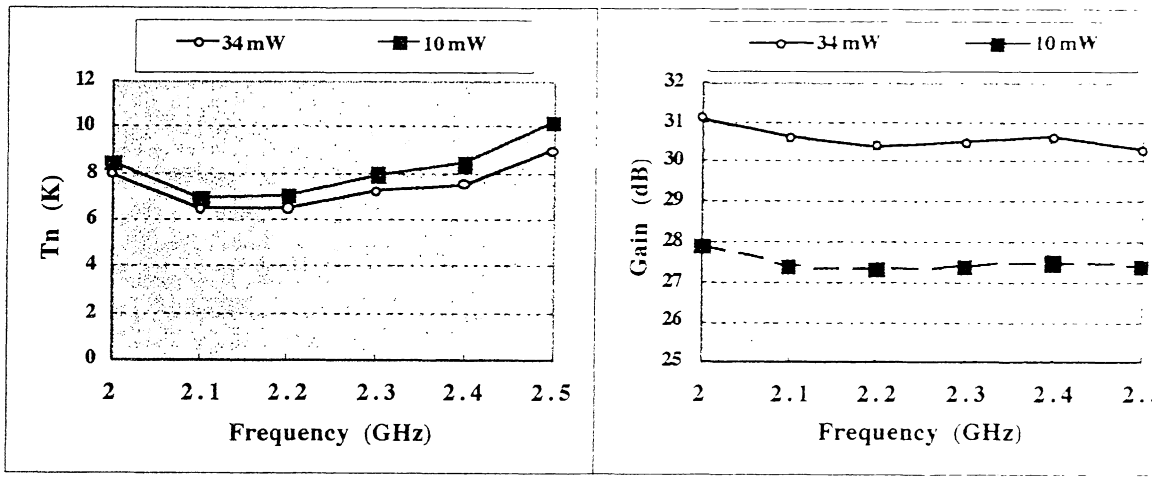

Fig.2 The noise temperature and gain of a 2.0-2.5 GHz amplifier with two HEMT devices (MGF4318D). Two different bias conditions are applied. In case(i), Vd= 2 V, Id1= 7 mA, and Id2= 10 mA, which means the power dissipation of 34 mW. In case(ii), Vd= 1 V, Id1= 5 mA, and Id2= 5 mA, which means the power dissipation of 10 mW. The noise temperature does not deteriorate so much even when the DC power dissipation is largely reduced.

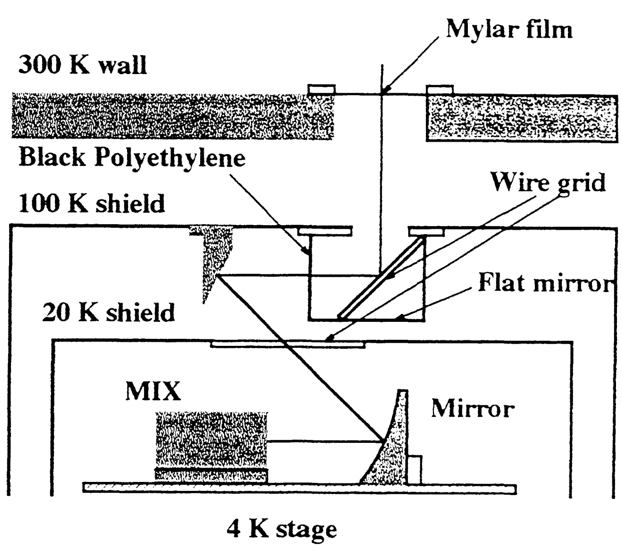

Fig.3 Thermal radiation from the RF window is one of major heat loads to the 100 K stage. This figure shows one possible method to reduce it. Submillimeter RF will look at a black-polyethylene film (IR filter) which has a high IR emissivity, but IR will look at a metal surface which has a low IR emissivity, so the IR coupling between 300 K and 100 K will be reduced.

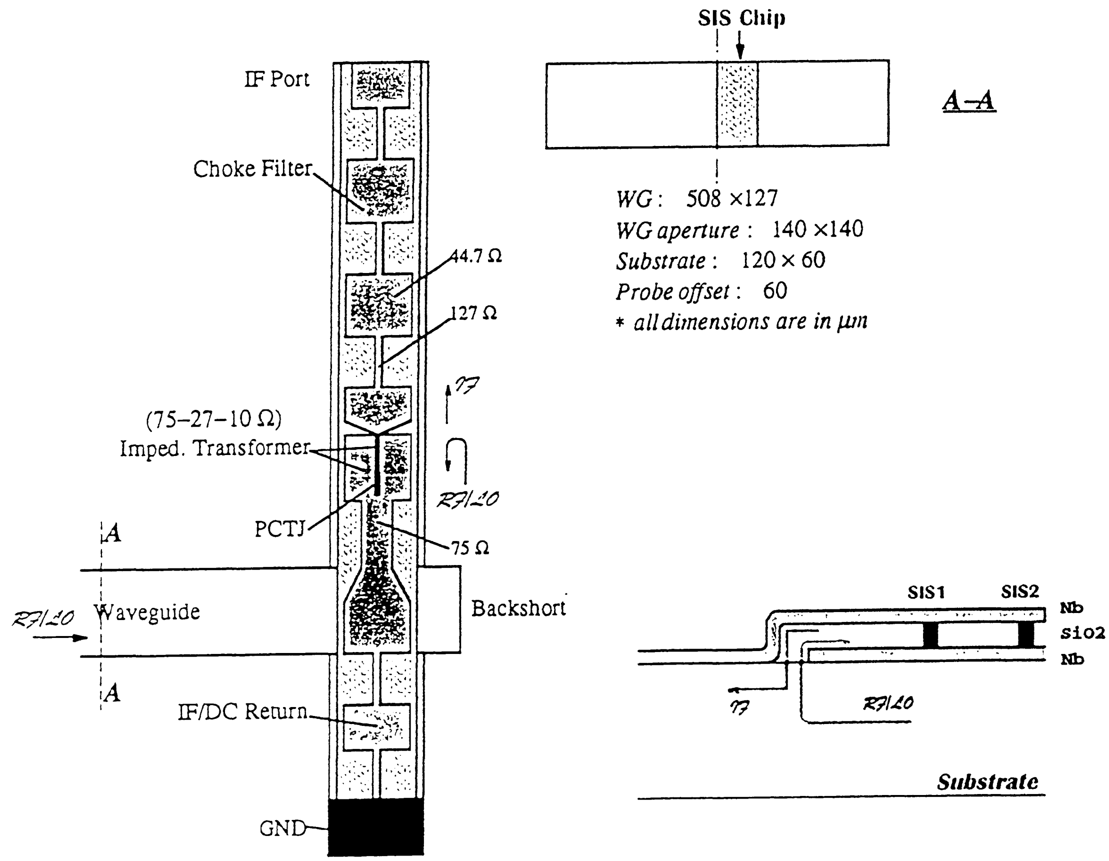

Fig. 4 Schematic drawing of the 500 GHz waveguide-type SIS mixer, which is used in the present experiment. Broad-band characteristics more than 20 % is predicted in a simulation based on the FEM (Finite Element Method) with a fixed backshort.