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A cryosystem for cartridge-type SIS receivers

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Abstract

We developed a cryosystem, which houses 3 cartridge-type superconductor-insulator-superconductor (SIS) receivers at millimeter and submillimeter wavelengths. Since it was designed for a prototype receiver of the Atacama Large Millimeter/ submillimeter Array (ALMA), high stability, accurate alignment and easy handling were required. To accomplish these requirements, the cryosystem included following technologies: 1) thermal switches without screws for receiver cartridges. 2) center pipe structure to reduce vacuum and gravitational deformations. 3) bellows structures to reduce mechanical vibrations of a cryocooler 4) gold plated GFRP structures to reduce thermal emission. 5) GM 3 stage cryocooler with a He pot to reduce the thermal ripple. The cryostat has a cylinder-like shape with an inner diameter of 500 mm, an inner height of 510 mm, and a volume of $\approx$ 100 liters. Thermal conductance of the thermal switches showed very good performances of 1.7 W K^{-1} at 4K stage, 5.6 W K^{-1} at 12 K stage, and 3.3 W K^{-1} at 100 K stage, respectively. The mechanical vibration on the 4 K stage of the cartridge was reduced one-tenth, as small as $\approx$ 2 μm peak to peak, compared to that on the coldhead of $\approx$ 20 μm peak to peak. Temperature ripple on the cartridge was reduced as small as 2 mK peak to peak

which corresponding to about one-forth of the ripple on the coldhead with a He pot.
Key words: instrumentation: ALMA, submillimeter, receiver, cartridge

1. Introduction

Low noise superconductor-insulator-superconductor (SIS) receivers have been developed for submillimeter-wave astronomical observations (e.g. Kooi et al. 1994, Carlstrom & Zmuidinus 1996), and the noise temperatures of these SIS tunneling junction mixers have reached a few times of quantum limit (e.g. Karpov et al. 1996). The sensitivity of the receivers for an astronomical signal, however, has limited by the stability of the receivers which mainly affected by the mechanical vibration of a cryocooler rather than the noise temperature of the mixer itself (e.g. Sekimoto et al. 2001b). In order to promise receiver high performance at submillimeter wavelengths, techniques such as a shock absorbing structure for mechanical vibrations, an accurate alignment to optimize receiver optics to an antenna are required. To make optics between a feed horn and the subreflector simple and compact, the Cassegrain focus is suitable for the receiver. To keep a precise alignment of the optics, the cryosystem have to reduce gravitational deformations.

In addition, since a number of telescopes (e.g. a number of antennae and receiver) will have been large like the Atacama Large Millimeter/ submillimeter Array (ALMA), an easy maintenance of the receivers has become much important. The ALMA is an international collaboration to construct and operate a millimeter/ submillimeter wavelength telescope comprised of 64 $\times$ 12 m high precision antennae at the northern Chile from 2010. Each antenna can contain a high sensitive receiver which consists of 10 frequency bands covering from 7 mm to 0.3 mm in wavelength (Lamb et al. 2001). To produce and operate several hundred receivers, a cartridge type receiver has introduced (Wild et al. 2002). A cartridge receiver corresponding to a frequency band is equipped with cooled optics, SIS mixers, IF amplifiers and it works as a receiver under a cooled down condition. The interface of the cartridge is clear and compatible with each other, and it enable worldwide receiver engineers to develop cartridges independently.

The cryosystem is also designed to be installed to an telescope, Atacama Submillimeter Telescope Experiment (ASTE, Sekimoto et al. 2001a), which is a 10 m submillimeter telescope developed as a prototype antenna of the Large Millimeter and Submillimeter Array (LMSA, Kawabe et al. 1999). The ASTE has been installed at Pampa la Bola (el. 4800 m) in northern Chile since March 2002. The ASTE was one of research & development activities for the LMSA and now is for the ALMA, and the cryosystem enable to test and operate the cartridge type receivers at the ALMA site.

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2. Cryosystem Design

2.1. Cryostat

The cross sectional view and the top view of the cryostat are shown in Figure 1. The vacuum vessel of the cryostat has a cylinder-like structure whose sizes are 508 mm in diameter of the body and 560 mm in height without the coldhead and the outer frame. The volume of the vessel is about 100 liters. The total mass of the vessel including the 3 cartridges, the coldhead and the frame but not including the compressor unit and the vacuum pump is 170 kg. The cryostat is composed of 3 stages, and each stage is connected to the 1st stage, the 2nd stage and the 3rd stage of the SUMITOMO GM 3 stage cryocooler, and is cooled down to 100K, 12K and 4K, respectively. Here, we define the name of these stages of the cryostat as "plate" to avoid confusion of names (See also in Figure 1). The 4 K plate is made of oxygen free copper (OFCu: C1050) of 8 mm thickness with gold plated. The 12 K and 100 K plates are made of Al with 8 mm thickness to reduce a weight. These plates are supported by a central support structure and 3 pencils of GFRP (G10) pipes with 12 mm in diameter and 3.5 mm thickness. These GFRP pipes are gold plated to reduce the emissivity, but only the pipes between 12K and 4K are not plated to cut the heat conduction through the thin gold layer. The central support structure is adopted to reduce a deformation of the cryostat under a vacuum condition. The structure consists of a rod of SUS (SUS304) 20 mm in diameter and a pipe of GFRP 60 mm in diameter and 5 mm in thickness, and the GFRP pipe is gold plated to reduce an emissivity. Because the central SUS rod is kept at room temperature even when the cryostat cools down, the shrinkage of the rod can be ignored. The multi layer insulators (MLIs) are inserted between the SUS rod and the GFRP pipe to reduce a thermal radiation from the central SUS rod. The simulation by using the FEM calculation software (ANSYS) shows that the amount of a maximum deformation of the vessel with the central support is 59 μm and is reduced to a factor of 1/8 compared to the vessel without central support. The sidewall of the cryostat is made of SUS with 4 mm thickness, and the top and bottom flanges are made of Al (Al6061-T6) with 20 mm thickness to reduce a weight. At the top flange, there are 4 windows. Three of them are for radio frequency (RF) signals, and the other is to measure a mechanical vibration on the coldhead. At a sidewall of the cryostat, there are windows for local oscillator (LO) signals. These windows are covered by the kapton sheet whose thickness are 12 μm for RF windows and 50 μm for LO windows. The cryostat has two radiation shields to reduce thermal radiation from the sidewall. One is 100 K radiation shield which connected to 100 K plate and the other is 12 K radiation shield which connected to 12 K plate. Both the radiation shields are made of 2 mm thick copper with Ni-plated. MLIs are not inserted between the sidewall and the shields to reduce the diameter of the cryostat. At the top and the sidewall of both the shields, there are RF and LO windows, and these windows are covered by the IR cut filter (ZITEX sheet of 0.1 mm in thickness) to reduce thermal radiations. The bellows structures are adopted to connect the cryocooler and the plates as shown in Figure 1 to reduce mechanical vibration of the cryocooler. Figure 2 is the photograph of the cryostat.

2.2. Cartridge

Two types of cartridge, one is $\phi 170$ mm cartridge, the other is $\phi 140$ mm cartridge, can be installed to the cryostat. Because the interface of the cartridge is compatible to the ALMA, cartridges designed for the ALMA can be installed to the cryostat. Both types of cartridge are composed of 3 stage structure. The interface of the $\phi 170$ mm cartridge is following: The lower stage which is cooled down to 100 K has a diameter of 170.0 mm and the separation between the bottom flange and the surface of the 100 K stage is 120.0 mm. The middle stage which is cooled down to 12 K has a diameter of 169.5 mm and the separation between the surface of the 100 K stage to the surface of the 12 K stage is 80.0 mm. The upper stage which is cooled down to 4 K has a diameter of 169.0 mm and the separation between the surface of the 12 K stage and the surface of the 4 K stage is 80.0 mm. The cross sectional drawing and the photograph of the $\phi 170$ mm cartridge are shown in Figure 3. The $\phi 140$ mm cartridge has 3 stages whose diameters are 140.0 mm, 139.5 mm, and 139.0 mm and the separations between stages are same as these of the $\phi 170$ mm cartridge.

The support structures of the cartridge are pipes of 60 mm in diameter and 5 mm in thickness made of GFRP. The pipes of 12 K - 100 K and 100 K - 300 K are gold plated to reduce thermal radiation of the structures. The pipe of 4 K - 12 K is not plated, since the radiation from such a low temperature is negligible small and the thermal conductance from a thin gold layer should be cut. The 4 K stage of the cartridge is made of OFCu to keep high thermal conductivity, and the 12 K and 100 K stages are made of Al to reduce a weight. The alignment of the cartridge is defined by the bottom flange. Each stage is cooled through the thermal switch which connected to each plate. The advantages of the structure are following: 1) each stage has a wide outer space and is useful for installation of equipments such as low-noise amplifier. 2) the stages can be machined within a distortion of 0.01 degree to the bottom flange after the structure is assembled. 3) the structure has enough strength against the gravitational deformation. The displacement of the cartridge with 1 kg weight on the 4 K stage is calculated to be 3 μm when the cryostat is horizontally inclined by using the FEM calculations (ANSYS).

2.3. Thermal switch

A thermal switch has been developed for the ALMA receiver to simplify exchanges of the cartridges and to keep high thermal conductance between the cartridges and the cryocooler (Sugimoto et al. in prep.). The switch don't have to use any screws. The cross-sectional drawing and the photograph of the thermal switch are shown in Figure 4. The switch is composed of a crown-like ring made of OFCu and a crumping belt, which is a metal spring or Nylon ring. The inner radius of the OFCu ring is consistent to the diameter of the cartridge with a tolerance of 20 μm, and the ring is divided to 60 pieces, like a comb. The inner surface of the ring which contact to the stage of the cartridge is machined as smooth as the surface roughness of 10 μm to increase a contacting area. We reduce the thickness of the bridge structure of the switch between the contacting surface of the ring and the plate of the cryostat in order to mitigate the vibration from the coldhead, and the thickness of the bridge is as thin as 0.3 mm.

In the case of a metal spring, the thermal contact between the cartridge and the OFCu ring is obtained by binding tight for elasticity of the spring. We can adjust the contact forces by selecting the various elasticitye of springs. In the case of Nylon belt, the contact is obtained by using the difference of thermal expansion coefficients between OFCu and Nylon. At a room temperature, the inner diameter of the Nylon ring is 0.1 mm larger than the outer diameter of the OFCu ring, and the Nylon ring can be easily attached and detached. On the other hand, strong thermal contacts are obtained under low temperature conditions (4K, 12K, and 100K). This is because the thermal expansion coefficient of Nylon is about 10 times larger than that of OFCu. Another important advantage of our thermal switch is that the switch requires small space with an extra width of 12.5 mm for a cartridge. This makes it possible to realize a compact cryostat.

2.4. GM 3 stage cryocooler and compressor unit

We used a SUMITOMO GM 3 stage cryocooler for the cryostat. It has a cooling capacity of 0.75 W at 3.80 K, 10 W at 12.8 K, and 40 W at 98 K under a condition of horizontal orientation. The cryocooler is equipped with a He pot to stabilize the temperature (Sekimoto et al. 2001b). It can reduce the temperature ripple from 200 mK to 20 mK under a 4 K operation. A compressor is selected which can be used under a low atmospheric pressure (550 hPa) and outdoor conditions, have high reliability and easy to maintenance, which is required for the ALMA.

2.5. Thermal Calculation

We calculated the thermal load for the cryosystem. All the plates of the cryostat and the stages of cartridges and thermal shields are cooled by the SUMITOMO GM 3 stage cryocooler. On the 4 K stage of the cartridges, the SIS mixer and the cooled optics are mounted. At the stage, the main thermal inputs are thermal conductance from the GFRP pipes of the cartridges and the central support. And another major inputs are thermal radiation from 12 K shield and central pipe. Furthermore, there are heat inflows from bias cables, IF cable, sensor cables such as for a temperature monitor and a heater, etc. The total heat flow under the condition that 3 cartridges are inserted is expected to be 0.34 W. At the 12 K stage, thermal inputs are mainly from the heat conduction from the GFRP pipes, and small fraction of the flow is from 100 K thermal radiation shield. The LNAs are also mounted on the 12 K stage of the cartridge. The total heat flow is expected to be 2.7 W. And at the 100 K stage, the most part of the thermal inputs is from the radiation of the inner wall of the cryostat. The heat conduction from GFRP supports also become large. The total amount of heat flow is expected to be 35 W. The thermal balance for the cryostat is summarized in Table 1.

3. Results

3.1. Cooling time and temperature distributions of the cryostat

Temperature distributions in the cryostat were measured with silicon diodes by the Lake Shore Cryotronics, Inc. We used the sensors of DT471, DT470, and DT670. The cooling time of the cryostat, the time which 4 K stage reach the lowest temperature and become a stationary state, was 12.5 hours. Here, both the ϕ170 mm cartridges were installed and the ϕ 140 mm cartridge port was vacant and covered with the Cu plate to cut 300 K thermal radiation from the bottom flange. In the case of only one cartridge inserted and the other two ports are vacant and the case of 3 cartridge inserted, the cooling times is 12 hours and 13 hours, respectively. Figure 5 shows the cooling time of the cryostat with 2 $\times$ 170 mm cartridges. After 12.5 hours cooling, the temperature distributions of the cryostat became as shown in Figure 6. The temperature of the 4 K stage on the cartridge reached as low as 3.5 K, and is low enough to operate SIS receivers. The difference of the temperature between on the coldhead and on the 4K stage of cartridge was 0.1-0.2 K. The temperature of the lower plate (100 K plate) was 76.5 K and the difference between the plate and the stage of the cartridge was about 2 K. Whereas, the 1st stage of the cryocooler was about 56.0 K. A large difference between cryocooler and the plate ($\sim$ 20 K) existed. On the other hand, the temperature of the middle plate (12 K plate) was 13.8 K and the difference between the plate and the stage of the cartridge was about 0.4 K. The 2nd stage of the cryocooler was 11.2 K. The difference between cryocooler and the plate ($\sim$ 3 K) was also large. These large differences between the plate and the each stage of cryocooler are due to bad thermal conductance of Al and the rough contacts between bellows structures and the cryocooler. The temperature of the center pipe between 100 K and 12 K stages was 52.3 K, that between 12 K stage and 4 K stage was 8.4 K, and that above the 4 K stage was 10.2 K.

Thermal ripple on the 4K stage of the cartridges is shown in Figure 7. The 1 Hz variations which comes from the stroke of the cryocooler were also monitored. The sampling interval including the processing time of the computer was about 80 msec. The time variation of the temperature on 4K stage was reduced as a factor of 1/4 compared with the variations on the top of the coldhead. Since the short time variation of temperature related to a heat capacity, the variation of the ALMA receiver will be reduced.

3.2. Thermal conductance of the thermal switch

We tested the thermal switch system by using Nylon ring as a crumping belt. This switch with Nylon ring can fulfill the function between 2 K and 100 K. The thermal conductance of the switch was measured by following: 1) The resistances of 50 Ω were placed on the 4 K, 12 K, and 100 K stages of the cartridge. 2) The temperatures on the cartridges (T_A) and the root of the thermal switch (T_B) were measured by using silicone diodes. 3) The relationship between the temperature difference (ΔT_A - ΔT_B) and the heat load (Watt) were measured by changing the electric current intensity. The measured thermal conductance of the switch is fairly good, and is 1.7, 5.6, 3.3 W K^{-1} for 4, 12, and 100 K stages, respectively. The result is summarized in Table 2. The detailed discussions about the thermal switch will be reported in another paper (Sugimoto et al. in prep.).

3.3. Mechanical vibration of the cryostat

The amounts of vibration along both vertical axis and horizontal axis on the cartridge were measured by using the optical laser (Keyence inc., LK-080). The vertical vibration on the top of coldhead was as large as 45 μm (peak to peak) at 300 K, and was reduced to be 20 μm (peak to peak) at 4 K. On the other hand, the amount of the vibration on the 4 K stage of the cartridge was 15 μm (peak to peak) at 300 K, and 2 μm (peak to peak) at 4 K. On the contrary, the amount of the horizontal vibration on the top of the 4K stage of the cartridge was 6 μm (peak to peak). This means that the part of the vertical vibration on the coldhead converted to a horizontal vibration. Both the mechanical vibrations at the top of coldhead and on the 4K cartridge under 4 K condition are shown in Figure 8. By adopting the bellows structure which connect each the stage of the cryocooler and the plates, the mechanical vibrations of the coldhead with 1 Hz were successfully reduced.

4. Summary

We have developed a prototype receiver for the ALMA. Here, we summarized the main results and features of the cryosystem.

1. The easy handling cryosystem with the 3 cartridge-type receivers: The cryosystem make it easy to exchange receivers, and it makes receiver engineers possible to develop receivers at their facilities and to assemble the receivers to our cryosystem.
2. The thermal switch comprised of the OFCu ring and the clumping belt: The performance of the thermal switch is fairly good. The thermal conductance of these switches are 1.7 W K^{-1} at 4K stage, 5.6 W K^{-1} at 12 K stage, and 3.3 W K^{-1} at 100 K stage, respectively. Not only high thermal conductance, but also low mechanical vibrations were achieved by adopting the thin bridge structure.
3. The center pipe structure of the vessel against for vacuum and gravitational deformations: By adopting the support structure, we reduced a deformation of the vessel as a factor of 1/8 compared to the vessel without a central support. This low deformation of the vessel make it possible to achieve an accurate alignment of the optics.
4. The bellows structures against for mechanical vibrations: The vertical vibration on the cartridge was reduced as a factor of 1/10, as small as 2μm (peak to peak). This low vibration would reduce the variations of the gain of the submillimeter receivers.

5. The temperature ripple on the 4 K cartridge was also reduced as a factor of 4 compared to that on the coldhead. The short time temperature ripple on the cartridge with 1 Hz is as small as 2 mK (peak to peak).

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Table 1. Summary of the thermal calculation of the cryostat.

Temp. Stage	Heat Flow	3 cartridges [W]	Cryostat [W]	Total [W]
100K	Radiation	4.05	22.36	26.41
	Conduction	4.21	4.56	8.77
	Generation of heat	0.15	0.03	0.18
12K	Radiation	0.05	0.10	0.15
	Conduction	1.41	0.81	2.22
	Generation of heat	0.36	0.02	0.38
4K	Radiation	0.01	0.08	0.09
	Conduction	0.06	0.05	0.11
	Generation of heat	0.15	0.0	0.15

Table 2. Thermal conductance of the thermal switches.

Temperature Stage	4 K	12 K	100 K	[unit]
Conductance (calc.)	1.9	5.4	3.11	$W\ K^{-1}$
Conductance (measure)	1.7	5.6	3.3	$W\ K^{-1}$
Estimated heat load	50	120	50	mW
ΔT^*	0.03	0.02	0.02	K

$^*\Delta T$ is an expected temperature loss originated in the thermal switch.

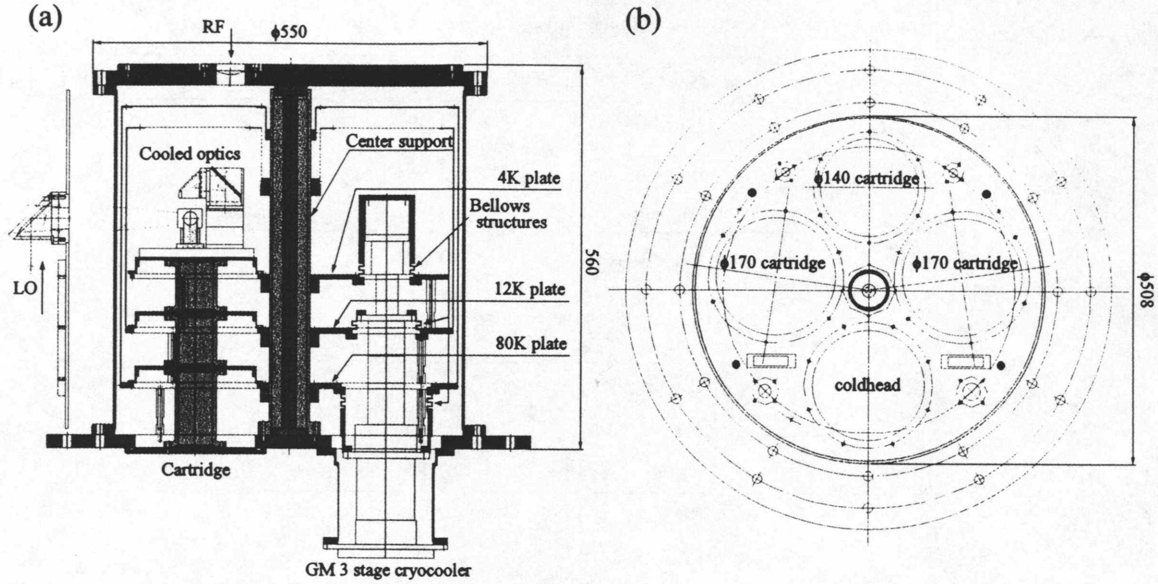

Fig. 1. (a) A cross sectional view of the cryostat. The cryostat is composed of 3 stages which named "plates", 4 K, 12 K, and 100 K from up to down. The support structure is at the center of the vessel. The bellow structures to reduce mechanical vibrations of the cryocooler are seen between the coldhead and the plates. (b) A top view of the cryostat. Three cartridges, one is ϕ140 mm, and the others are ϕ170 mm, can be inserted simultaneously.

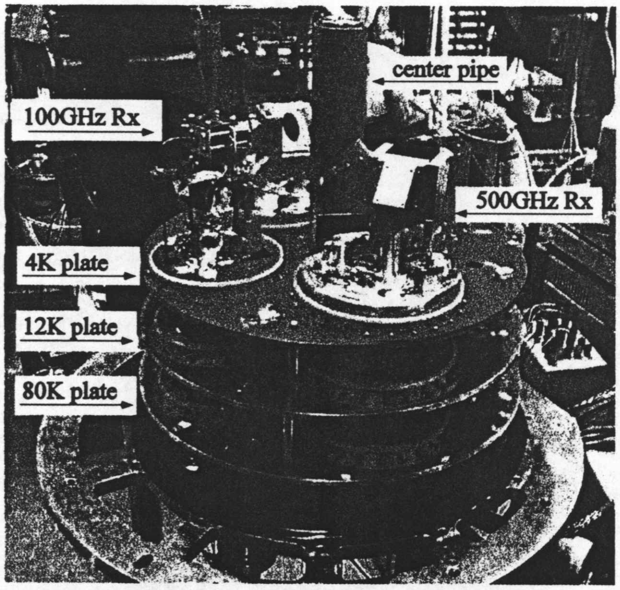

Fig. 2. A photograh of the cryostat without radiation shields. The cooled optics of the Band 8 (385-500 GHz) receiver can be seen on the front cartridge, and the feed horn of the Band 4 (125-163 GHz) receiver can be seen on the left hand side cartridge.

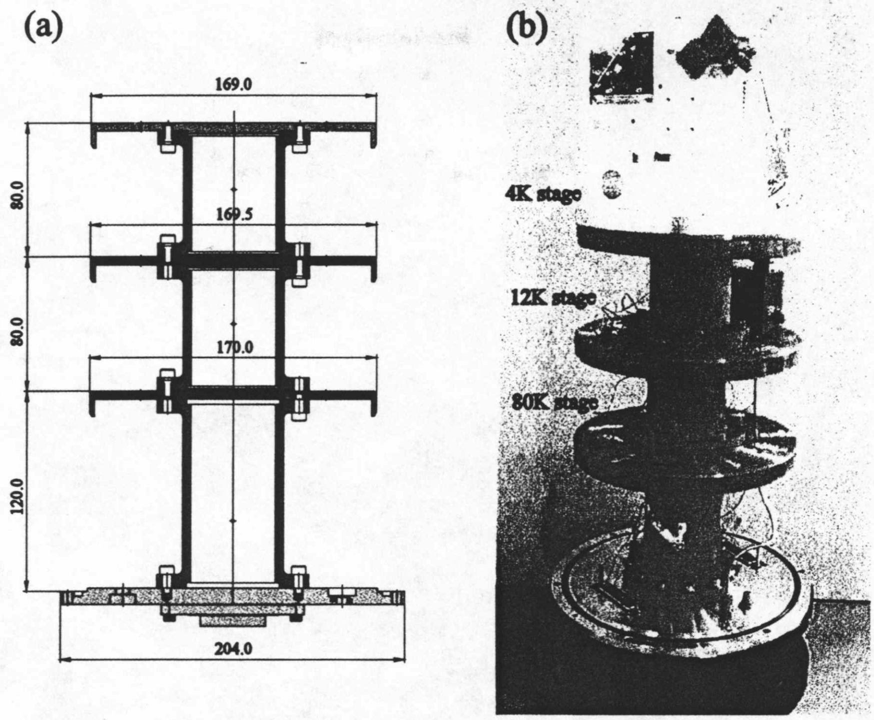

Fig. 3. (a) A cross-sectional view of the ϕ170 mm cartridge. (b) A photograph of the cartridge with the Band 8 (385-500 GHz) SIS receiver. The LNA can be seen on the middle stage of the cartridge.

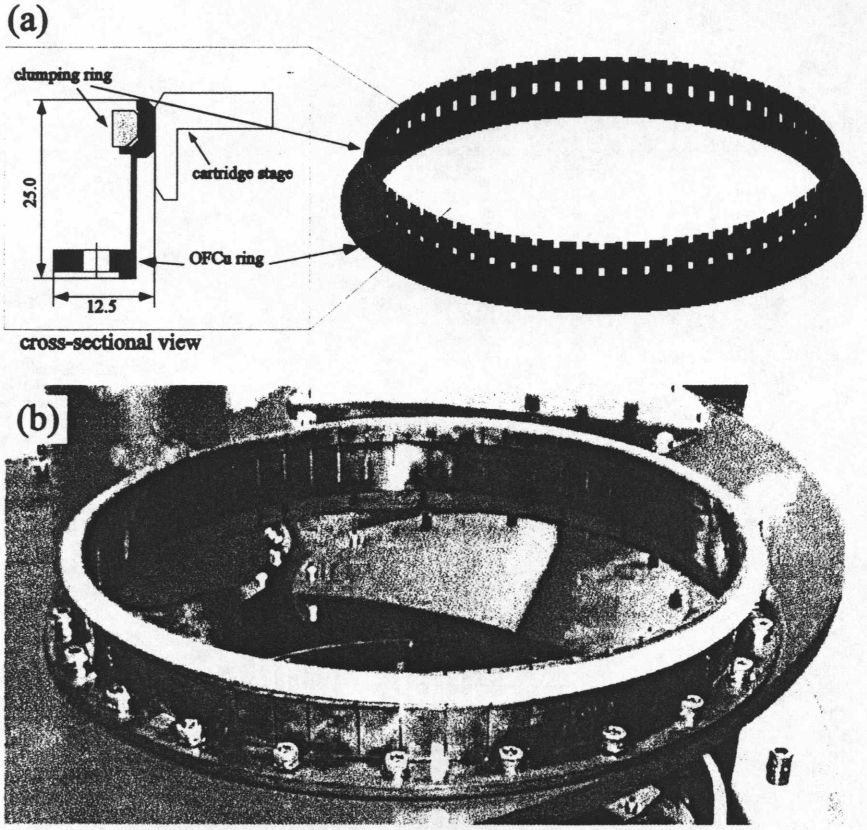

Fig. 4. (a) A schematic drawing of the thermal switch. The inner ring is made of an oxygen free copper (OFCu) with a 170 mm inner diameter. The ring is divided to 60 pieces, and is surrounded by the Nylon clumping ring (or metal spring). (b) A photograph of the thermal switch with the Nylon clumping ring.

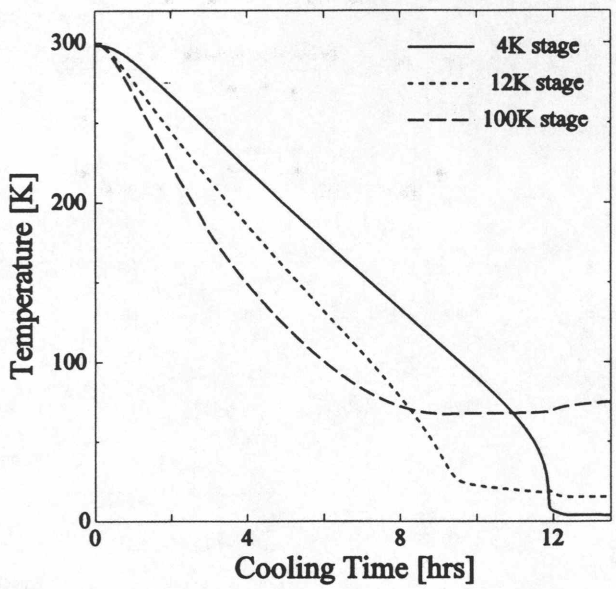

Fig. 5. A cooling time of the cryostat. It takes 12.5 hours to reach 4 K stage to the lowest temperature and to be stabilize.

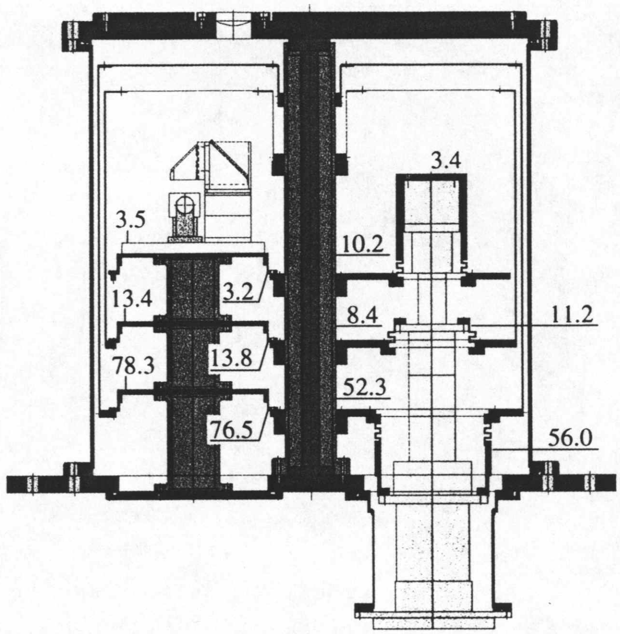

Fig. 6. Temperature distributions in the cryostat under a cooled down condition. Unit: [K]

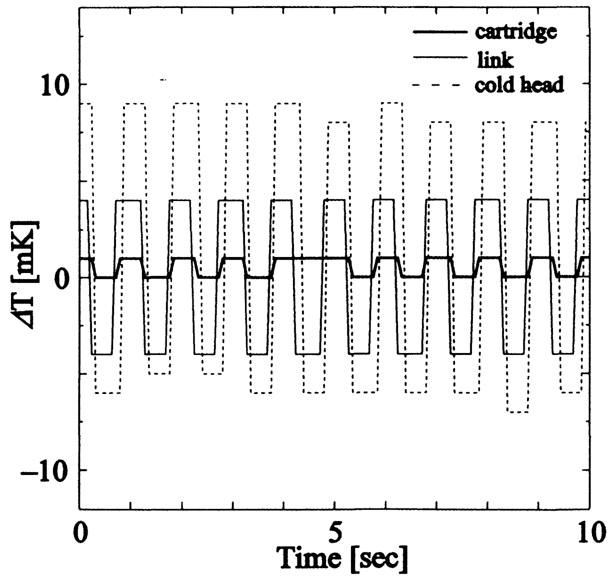

Fig. 7. Temperature ripple on the 4K stage, the 4K plate and beside the 4K thermal swith.

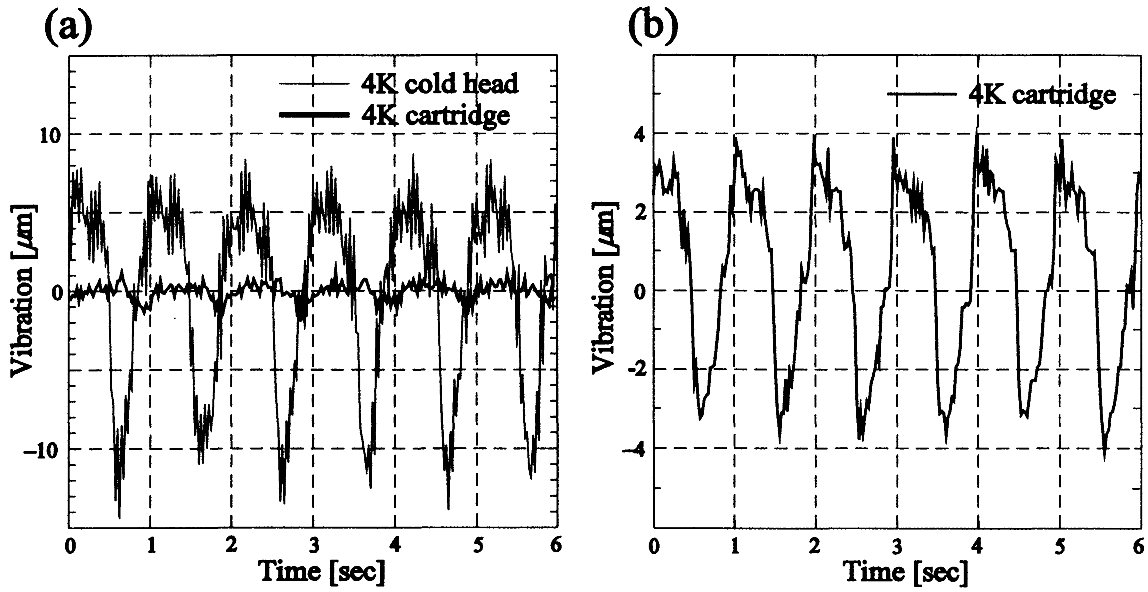

Fig. 8. (a) Mechanical vibrations along the vertical axis on the coldhead and on the cartridge at 4K. 1 Hz vibration can be seen, and the amount of vibration on the cartridge is reduced of factor of 1/10 compared to that on the coldhead. (b) A mechanical vibration along the horizontal axis on the cartridge at 4K.