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Plug-In Cryogenic System for Cartridge-Type SIS Receivers

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Abstract

We developed a cryogenic system, which houses 3 cartridge-type superconductor-insulator-superconductor receivers for millimeter and submillimeter wavelengths. Since it was designed as a prototype receiver of the Atacama Large Millimeter/ submillimeter Array (ALMA), high stability, accurate alignment, and easy handling were required. To meet these requirements, the cryogenic system included the following technologies: 1) a thermal link without screws for receiver cartridges; 2) a central support structure to reduce vacuum and gravitational deformation; 3) bellows structures to reduce mechanical vibration of the cryocooler; and 4) a 3-stage Gifford McMahon (GM) cryocooler with an He pot (temperature stabilizer) to reduce the thermal ripple. The cryostat and receiver cartridges are composed of three stages. The temperatures on the 4 K, 12 K, and 100 K stages of the cartridge are 3.5 K, 13.4 K, and 78.3 K, respectively. The thermal conductances of the thermal links showed high performances of 1.7 W K^{-1} at the 4 K stage, 5.6 W K^{-1} at the 12 K stage, and 3.3 W K^{-1} at the

100 K stage. The mechanical vibration on the 4 K stage of the cartridge was reduced to one-tenth, as small as $\approx 2\ \mu$m peak-to-peak, compared to that on the 4 K coldhead of the cryocooler, $\approx 20\ \mu$m peak-to-peak. The temperature ripple on the cartridge was reduced to as small as 2 mK peak-to-peak, which corresponds to one-seventh of the ripple on the 4 K coldhead with an He pot.

Key words: instrumentation: detectors — radio astronomy — miscellaneous

1. Introduction

Low-noise superconductor-insulator-superconductor (SIS) receivers have been developed for astronomical observations at submillimeter wavelengths (e.g. Carlstrom, Zmuidzinas 1996), and the noise temperatures of the SIS tunneling junction mixers have reached a few times of the quantum limit (e.g. Kooi et al. 1994; Karpov et al. 1995). Although the mixers are sufficiently sensitive, the sensitivity of a receiver for astronomical signals has been limited by various factors. One possible factor which limits the sensitivity is mechanical vibration that originates in the GM cryocooler, and might be more serious than the noise temperature of the mixer at submillimeter wavelengths (e.g. Kooi et al. 2000; Sekimoto et al. 2001b). In order to achieve a high receiver performance at submillimeter wavelengths, such techniques as a shock-absorbing structure to reduce the mechanical vibration, and an accurate alignment to optimize the receiver optics to an antenna are required. To make the optics between a feed horn and a subreflector simple and compact, the Cassegrain focus is suitable for the receiver. To maintain a precise alignment of the optics, the cryostat has to have minimal deformations under the vacuum condition with changing elevation angle.

In addition, since the number of antenna and receiver is becoming large as the Large Millimeter Submillimeter Array (LMSA, Ishiguro et al. 1998), the Atacama Large Millimeter/ submillimeter Array (ALMA), easy maintenance of receivers becomes important. The ALMA is an international collaboration project to operate a millimeter/ submillimeter wavelength telescope comprised of 64 × 12 m high-precision antennas in northern Chile from 2011. Each antenna can house a highly sensitive receiver consisting of 10 frequency bands covering from 10 mm to 0.3 mm in wavelength (Brown et al. 2002). To produce and operate several hundred receivers, a cartridge-type receiver was introduced (e.g. Wild et al. 2002). A cartridge-type receiver equipped with cooled optics, SIS mixers and IF amplifiers works under a cooled condition. The interface of the cartridge is simple and compatible with each other, and allows worldwide receiver engineers to develop cartridge-type receivers independently.

Our cryogenic system houses 3 cartridge-type receivers with the same interface to the ALMA receivers, and is designed to be installed in a telescope, the Atacama Submillimeter Telescope Experiment (ASTE, Sekimoto et al. 2001a), which is a 10 m submillimeter telescope developed as a prototype antenna of the LMSA (Ukita et al. 2000). The ASTE was installed at Pampa la Bola (elevation 4800 m) in Atacama, Chile in 2002 March. It plays a role as one of the research and development activities for the LMSA, and now for the ALMA. The cryogenic system enables one to test and operate the cartridge-type receivers at the ALMA site.

2. Cryogenic System Design

2.1. Cryostat

A cryostat was designed to fulfill cryogenic requirements, such as a short cool-down time, low temperature, tough structure to vacuum and gravitational deformation, and high stability to temperature ripple and mechanical vibration. Since the upper cabin of the ASTE where the cryostat is installed has only a space of ϕ 600 mm, the cryostat was designed to be compact. A cross-sectional view and a top view of the cryostat are shown in figure 1. A vacuum vessel of the cryostat forms a cylindrical structure whose body dimensions are 508 mm in diameter and 560 mm in height without a cryocooler and an outer frame. The total mass of the cryostat, including the 3 cartridges, the cryocooler, and the frame, is 170 kg.

The cryostat is composed of 3 stages, and each stage is connected to the 1st stage, 2nd stage, and 3rd stage of the 3-stage Gifford McMahon (GM) cryocooler (Sumitomo RDK 3ST), and is cooled to 100 K, 12 K, and 4 K, respectively. We define the name of these stages of the cryostat as "plate" (see also in figure 1). The 4 K plate is made of oxygen-free copper (OFCu: C1050) of 8 mm thickness and is plated with gold. The 12 K and 100 K plates are made of aluminum (Al) of 8 mm thickness to reduce the weight. These plates are supported by a central support structure and 3 pencils of GFRP (G10) pipes of 12 mm in diameter and 3.5 mm in thickness. These GFRP pipes are plated with gold to reduce the emissivity, but the pipes between 12 K and 4 K are not plated to avoid heat conduction through the gold layer.

A central support structure is adopted to reduce the deformation of the cryostat under vacuum conditions. The support structure consists of a rod of SUS (304) 20 mm in diameter and a pipe of GFRP 60 mm in diameter and 5 mm in thickness. Because the central SUS rod is kept at room temperature even when the cryostat cools down, shrinkage of the rod can be ignored. Multi-layer insulators (MLIs) are inserted between the SUS rod and the GFRP pipe to reduce thermal radiation of the SUS rod. A simulation using a finite element model (FEM) calculation software (ANSYS) shows that the amount of the maximum deformation of the vessel with a central support is 59 μm, and is reduced by a factor of 1/8 compared to one without a central support.

The side wall of the cryostat is made of a SUS of 4 mm thickness, and the top and bottom flanges are made of Al (Al6061-T6) of 20 mm thickness to reduce the weight. There are 4 windows at the top flange. Three of them are for radio-frequency (RF) signals, and the other is to measure mechanical vibrations on the cryocooler. In the side wall of the cryostat, there are windows for local oscillator (LO) signals. These windows are covered by a thin film made of polyamide (Kapton), 12 μm thickness. The cryostat has two radiation shields to reduce the thermal radiation from the outer shell. One is a 100 K radiation shield connected to a 100 K plate, and the other is a 12 K radiation shield connected to a 12 K plate. Both radiation shields are made of Ni-plated copper with a thickness of 2 mm. Since the cooling capacity of the 1st stage of the cryocooler is sufficient to cool the cryostat, MLIs are not inserted between the side wall and the shields. This allows the diameter of the cryostat to be reduced, and enables a compact cryostat to be realized. At the top and the side walls of both shields, there are RF and LO windows which are covered by an IR cut filter (Zitex sheet of 0.1 mm in thickness) to reduce the thermal radiation. In order to reduce mechanical vibration of the cryocooler, bellows structures are adopted to connect the cryocooler and the plates, as shown in figure 1. Figure 2 is a photograph of the cryostat with 3 cartridge-type receivers.

2.2. Cartridge Structure

The interface of the receiver cartridges for the ALMA was proposed by the Rutherford Appleton Laboratory (RAL) in UK (Orlowska et al. 2002). A cartridge structure, which we proposed, is supported by the central pipe (column-type), and the interface is compatible to the ALMA receiver cartridges. In comparison with our cartridge, the cartridge proposed by the RAL is supported by the outer shell (closed-type). Although the closed-type cartridge is stronger against gravitational deformation, decomposition of the cartridge is indispensable to assemble receivers. On the other hand, the column-type cartridge can be assembled without any decomposition of the cartridge. To realize easy assemblage of the receivers, we adopted the column-type for structure for the cartridge.

Two sizes of the cartridge, ϕ 170 mm and ϕ 140 mm, can be installed in the cryostat. Both types of cartridge are composed of 3-stage structures. A cross-sectional drawing and a photograph of our ϕ 170 mm cartridge are shown in figure 3; its interface is also denoted. The ϕ 140 mm cartridge has 3 stages whose diameters are 140.0 mm, 139.5 mm, and 139.0 mm, respectively. The separations between these stages are the same as those of the ϕ 170 mm cartridge. The support structures of the cartridge are pipes of 60 mm in diameter and 5 mm in thickness and made of GFRP. The pipes of 12 K − 100 K and 100 K − 300 K are plated with gold to reduce thermal radiation of the structures, and that of 4 K − 12 K is not plated, since the radiation is negligibly small and the thermal conductance through a thin gold layer should be cut. The 4 K stage is made of OFCu to maintain high thermal conductivity, and the 12 K and 100 K stages are made of Al to reduce the weight. The weight of the ϕ 170 mm cartridge without optics is 4.0 kg. The alignment of the cartridge is defined by the bottom flange. Each stage is cooled through thermal links connected to each plate. The advantages of our cartridge structure are the following: 1) each stage has a wide outer space, which is useful for the installation of equipment, such as low-noise amplifiers (LNAs); 2) the stages can be machined within an accuracy of $0^\circ.01$ to the bottom flange after the cartridge is assembled; 3) the structure possesses enough strength against gravitational deformation. The displacement of the cartridge with 1 kg weight on the 4 K stage under horizontally inclined conditions was calculated to be 3 μm using the FEM method (ANSYS).

Exchanging the cartridge is easy with the guiding device; also, we don't have to open the flange of the vessel. The guiding device consists of metal rods, ball bearings, and a base on which the cartridge is set, and the cartridge slides smoothly along the rods.

2.3. Thermal Link

A thermal link is equipment which connects between the coldhead of the cryocooler and the target which needs to be cooled with high heat conductivity. A thermal link for the ALMA receiver was proposed by RAL to simplify the exchanges of cartridges and to maintain a high thermal conductance between the cartridges and the cryocooler (Orlowska et al. 2002). The RAL thermal link consists of a nylon clamping ring, a segmented copper clamping ring, and flexible braids. Although the RAL thermal link has high flexibility, it is complex and the heat conductivity is not large.

We have designed and developed a new and simple thermal link with high heat conductivity (Sugimoto et al. 2003). The link does not need any screws. A cross-sectional drawing and a photograph of the thermal link are shown in figure 4. The link is composed of 2 components: (1) a crown-like ring made of OFCu, and (2) a clamping belt, which is a metal spring or a nylon ring. The crown-like ring is divided into 60 pieces, like a comb. The inner surface of the ring, which comes into contact with the stage of the cartridge, is machined as smooth as a surface roughness of 10 μm to increase the area of contact. Thermal contact of the link is obtained by external pressure from a metal spring or a nylon ring. In the case of a metal spring, the thermal contact between the cartridge and the crown-like ring is accomplished by tight binding while considering the elasticity of the spring. We can adjust the contact forces by selecting various elasticities of the springs. In the case of a nylon belt, contact is accomplished by using the difference in the thermal-expansion coefficients between OFCu and nylon. At room temperature, the inner diameter of the nylon ring is 0.1 mm larger than the outer diameter of the OFCu crown-like ring, and the nylon ring can be easily attached and detached. On the other hand, strong thermal contacts are accomplished under low-temperature conditions (4 K, 12 K, and 100 K). This is because the thermal-expansion coefficient of nylon is about 10-times larger than that of OFCu. Another important advantage of our thermal link is that the link requires a small space with an extra width of 12.5 mm for a cartridge. This allows us to make a compact cryostat.

2.4. 3-Stage GM Cryocooler and Compressor Unit

We adopted a 3-stage GM cryocooler (Sumitomo RDK 3ST) for the cryogenic system.[1] 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 when the cryocooler is horizontally inclined. The cryocooler is equipped with an He pot to stabilize the temperature. This reduces the temperature ripple from 200 mK to 20 mK under 4 K operation (Sekimoto et al. 2001b). A compressor is selected for outdoor use under a low atmospheric pressure (550 hPa) at the ALMA site.

2.5. Thermal Calculation

We calculated the thermal load for the cryogenic system. All plates of the cryostat and stages of the cartridges and thermal shields are cooled by a 3-stage GM cryocooler. The SIS mixers and the cooled optics are mounted on a 4 K stage of the cartridges. At the 4 K stage, the main thermal sources are thermal conduction through the GFRP pipes of the cartridges and the central support structure. Other major sources are thermal radiation from the 12 K shield and central support structure. In addition, there is conduction through bias cables, signal cables, and sensor cables, such as those for the temperature monitor and the heater. The total heat flow of the 4 K stage under the condition that 3 cartridges are inserted is estimated to be 0.35 W. At the 12 K stage, thermal sources are mainly conduction through the GFRP pipes, and a small fraction of the flow is from the 100 K thermal radiation shield. The LNAs are also mounted on the 12 K stage of the cartridge. The total heat flow into the 12 K stage is estimated to be 2.75 W. At the 100 K stage, the primary thermal source is the radiation of the inner wall of the cryostat. The heat conduction through GFRP supports is also significant. The total amount of heat flow into the 100 K stage is calculated to be 35.4 W. The thermal load for the cryostat is summarized in table 1.

3. Results of the Measurements

3.1. Cooldown Time and Temperature Distribution in the Cryostat

The temperature distribution in the cryostat was measured with silicon diodes (DT471, DT470, DT670) from Lake Shore Cryotronics, Inc. under the condition that the power of the receivers shut down. The cooldown time of the cryostat, the time that it takes for the 4 K stage to reach the lowest temperature and become stationary, was 12.5 hours in a condition that both the ϕ 170 mm cartridges were installed and the ϕ 140 mm cartridge port was vacant and covered with the Cu plate to cut the 300 K thermal radiation from the bottom flange. In the case that only one cartridge is inserted and two other ports are vacant, the cooldown time is 12 hours. The cryostat fulfills this function, even in the case that one cartridge is inserted and two ports are vacant with the Cu plates to cut 300 K thermal radiation from the bottom flanges. With 3

[1] http://www.shi.co.jp/english/index.html

cartridges inserted, the time is 13 hours. Figure 5 shows the cooldown time of the cryostat with 2×170 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, low enough to operate SIS receivers. The difference in the temperature on the 4 K coldhead and on the 4 K stage of the cartridge was $0.1 - 0.2$ K. The temperature of the lower plate (100 K plate) was 76.5 K. The temperature of the middle plate (12 K plate) was 13.8 K. The 2nd stage of the cryocooler was 11.2 K. The difference between the cryocooler and the plate (~ 3 K) was large. This large temperature difference between the plate and each stage of the cryocooler was due to the thermal conductance of Al and the rough contact between the bellows structures and the cryocooler. The temperature of the central support structure between the 100 K and 12 K stages was 52.3 K, that between the 12 K stage and the 4 K stage was 8.4 K, and that above the 4 K stage was 10.2 K.

The thermal ripple on the 4 K stage of the cartridges is shown in figure 7. The 1 Hz variations coming from the stroke of the cryocooler were monitored. The sampling interval, including the processing time of the computer, was about 80 ms. The time variation of the temperature on the 4 K stage was reduced to a factor of 1/7 compared with the variations on the top of the cryocooler. Since the short-time variation of temperature is related to the heat capacity, the variation of temperature of the ALMA receiver can be decreased.

3.2. Thermal Conductance of the Thermal Link

We carried out tests of the thermal link system using a nylon ring as a clamping belt. This link with the nylon ring fulfills the function between 2 K and 100 K. The thermal conductance of the link was measured as follows: 1) A resistances of 75 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 link (T_{B}) were measured with silicone diodes. 3) The relationship between the temperature difference ($\Delta T_{\mathrm{A}} - \Delta T_{\mathrm{B}}$) and the heat load (in W) was measured by changing the electric-current intensity. The measured thermal conductance of the link was satisfactory, and was 1.7, 5.6, 3.3 W K^{-1} for the 4, 12, and 100 K stages, respectively. This result is summarized in table 2. A detailed description of the thermal link is reported by Sugimoto et al.

3.3. Mechanical Vibration of the Cryostat

The amplitude of mechanical vibration along both the vertical and horizontal axes on the cartridge were measured using an optical laser (Keyence Inc., LK-080). The vertical vibration on the top of the cryocooler was as large as 45 μm (peak-to-peak) at 300 K, and was reduced to 20 μm (peak-to-peak) at 4 K. The amplitude 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 other hand, the amplitude of the horizontal vibration on the top of the 4 K stage of the cartridge was 6 μm (peak-to-peak). This was due to the fact that part of the vertical vibration on the cryocooler converted to a horizontal vibration. Both mechanical vibrations at the top of the cryocooler and on the 4 K cartridge at 4 K are shown in figure 8. Adopting bellows structure which connects each stage of the cryocooler and the plates, the mechanical vibrations of the cryocooler with 1 Hz were reduced.

4. Summary

We have developed a cryogenic system with a high stability, an accurate alignment and easy handling. The cryogenic system can be applied not only to receivers in millimeter/submillimeter wavelengths, but also to detectors at optical and infrared wavelengths. We summarize the main results and advantages of the cryogenic system as follows:

1. An easy handling cryogenic system with the 3 cartridge-type receivers: The cryogenic system allows us to exchange receivers easily. The system makes it possible to develop receivers at worldwide facilities, and their receivers can be integrated in the system. The cooldown time of the cryostat is $\sim$ 13 hours and the attained temperature is $\sim$ 3.5 K on the 4 K stage of the receiver cartridge.
2. A thermal link comprised of a crown-like ring and a clamping belt: The thermal link accomplishes high performance. The thermal conductance of these links is 1.7 W K^{-1} at the 4 K stage, 5.6 W K^{-1} at the 12 K stage, and 3.3 W K^{-1} at the 100 K stage. A high thermal conductance and reduction of mechanical vibrations are achieved.
3. The central support structure of the vessel to reduce the vacuum and gravitational deformations: By using a support structure, we can reduce the deformation of the vessel up to a factor of 1/8 compared with a vessel without a central support. The low deformation of the vessel allows us to achieve an accurate alignment of the optics.
4. Bellows structures for mechanical vibrations: The vertical vibration on the cartridge is reduced up to a factor of 1/10, as small as 2 μm (peak-to-peak). This low vibration cuts down on the variations in the gain of the submillimeter receivers.
5. The temperature ripple on the 4 K cartridge is reduced by up to a factor of 1/7 compared with that on the coldhead. The ripple on the cartridge with 1 Hz is as small as 2 mK (peak-to-peak).

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

Temperature stage	Heat flow	3 cartridges [W]	Cryostat [W]	Total [W]
100 K	Radiation	4.05	22.36	26.41
	Conduction	4.21	4.56	8.77
	Generation of heat	0.15	0.03	0.18
12 K	Radiation	0.05	0.10	0.15
	Conduction	1.41	0.81	2.22
	Generation of heat	0.36	0.02	0.38
4 K	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 links.

Temperature stage	4 K	12 K	100 K	[unit]
Conductance (measured)	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 originating in the thermal link.

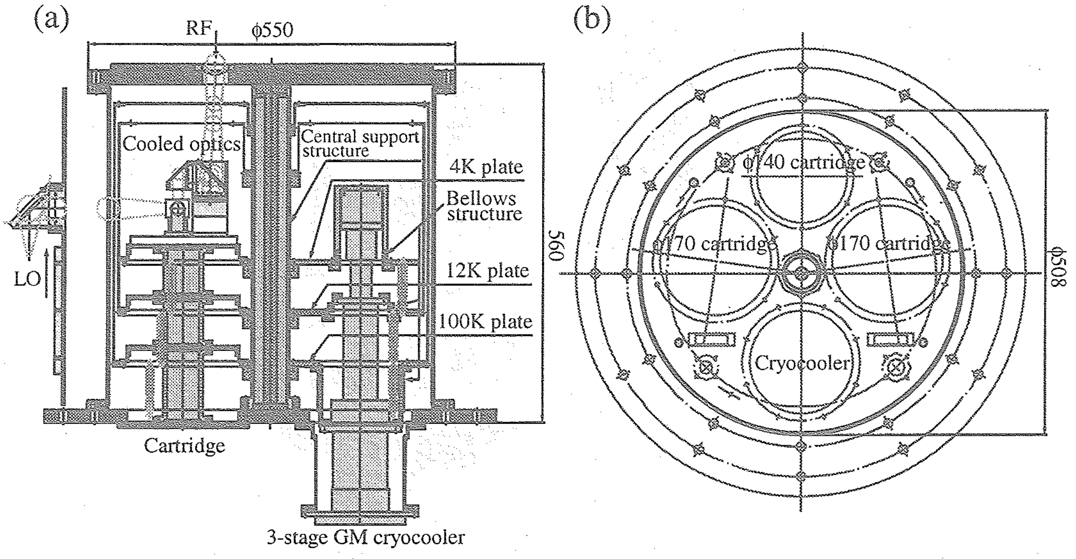


Fig. 1. (a) Cross-sectional view of the cryostat. The cryostat is composed of 3 stages named "plates", 4 K, 12 K, and 100 K from up to down. The central support structure is at the center of the vessel. Bellows structures to reduce mechanical vibrations of the cryocooler are located between the coldhead and the plates. (b) Top view of the cryostat. Three cartridges, one being ϕ 140 mm, and the others being ϕ 170 mm, can be installed simultaneously. The unit of both drawings is [mm].

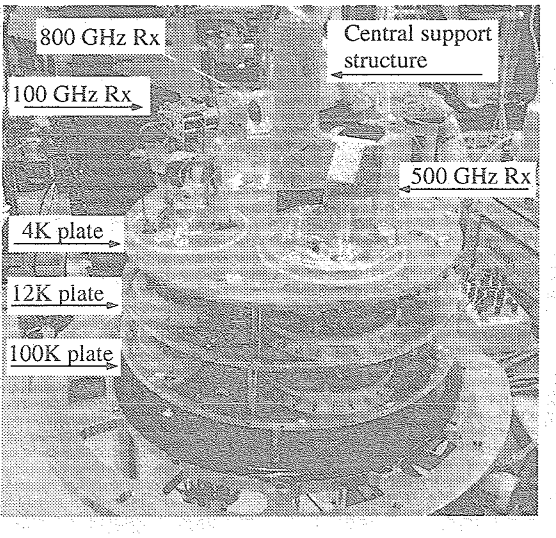
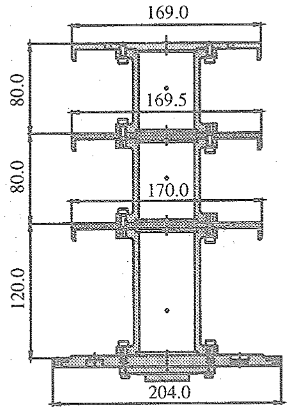


Fig. 2. Photograph of the cryostat without radiation shields. The cooled optics of the 500 GHz receiver can be seen on the front cartridge, and the feed horn of the 100 GHz receiver can be seen on the left side cartridge. The 800 GHz receiver optics can be seen behind the central support structure.

(a)



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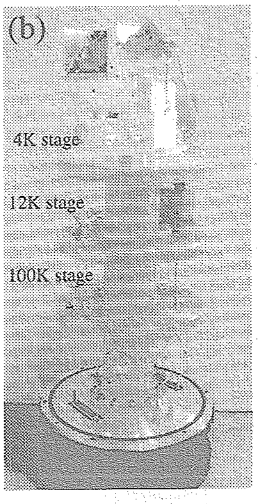
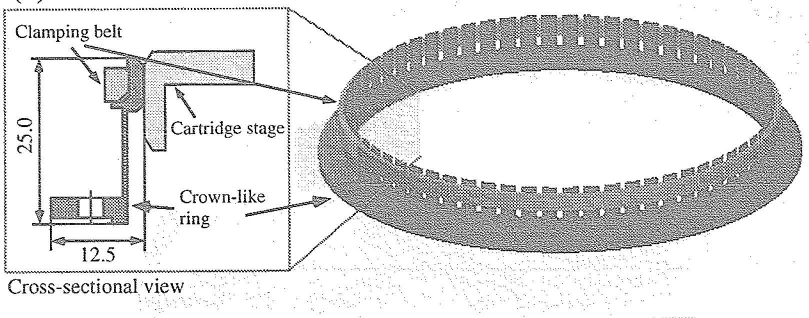


Fig. 3. (a) Cross-sectional view of the ϕ 170 mm cartridge. (b) Photograph of the cartridge with the Band 8 (385 – 500 GHz) SIS receiver. The LNA can be seen on the 12 K stage of the cartridge.

(a)



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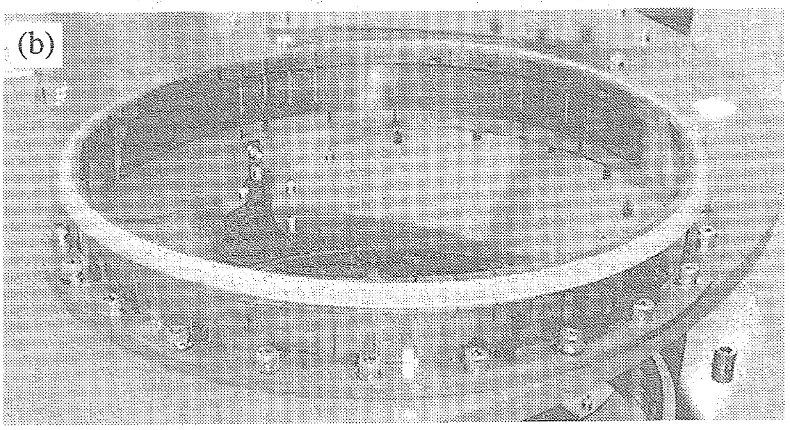

Fig. 4. (a) Schematic drawing of the thermal link. The inner ring is made of oxygen-free copper (OFCu) with a 170 mm inner diameter. The ring is divided into 60 pieces, and is surrounded by a clamping belt. (b) Photograph of the thermal link with a nylon clamping belt.

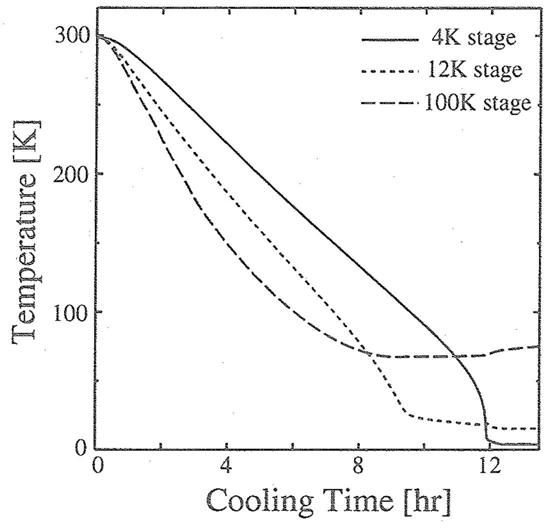

Fig. 5. Cool-down time of the cryostat. In the case of two ϕ 170 cartridges inserted, it takes 12.5 hours for the 4 K stage to reach its lowest temperature and to be stabilized.

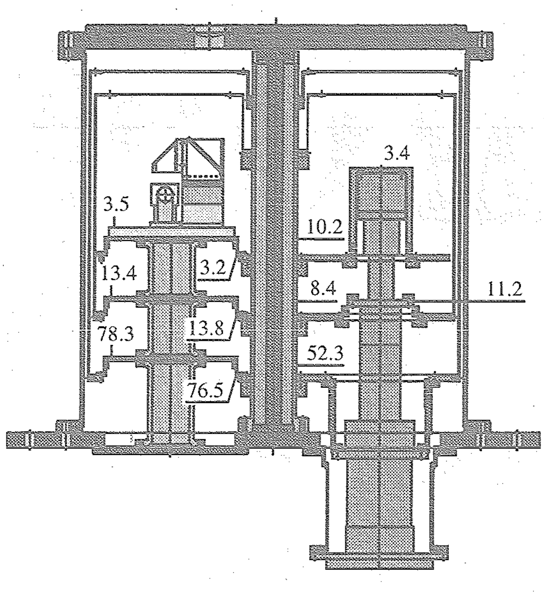

Fig. 6. Temperature distributions in the cryostat under cooled conditions. Unit: [K].

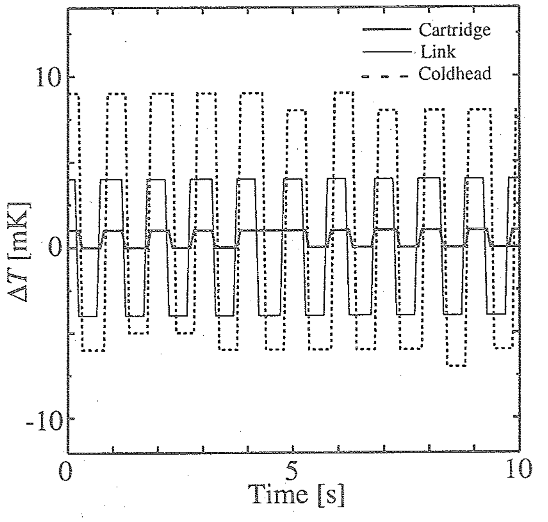

Fig. 7. Temperature ripples on the 4 K stage (on the cartridge), beside the 4 K thermal link and on the coldhead of the cryocooler. The resolution of the data is 2 mK for temperature and 80 ms for time.

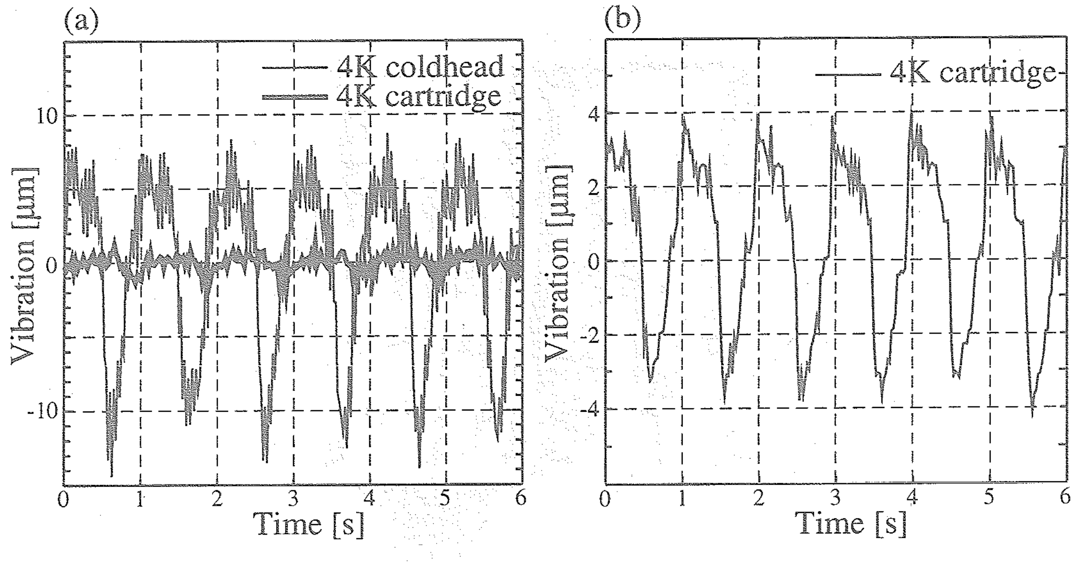

Fig. 8. (a) Mechanical vibrations along the vertical axis on the coldhead and on the cartridge at 4 K. A vibration of 1 Hz can be seen; the amplitude of the vibration on the cartridge is reduced to a factor of 1/10 compared to that on the coldhead. (b) Mechanical vibration along the horizontal axis on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