Development of a microcalorimeter array for the Diffuse Intergalactic Oxygen Surveyor (DIOS) mission

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ABSTRACT

We are developing a superconducting transition-edge sensor (TES) microcalorimeter array for the Diffuse Intergalactic Oxygen Surveyor (DIOS) mission. DIOS is a relatively small Japanese X-ray mission which will study large-scale distribution of the warm-hot intergalactic medium (WHIM) using O_{VII} and O_{VIII} emission lines. The satellite weighs about 400 kg equipped with a four-reflection X-ray telescope (FXT) and a TES microcalorimeter array (XSA). The design goal of the observing system is an effective area larger than 100 cm^2 at the oxygen line energy, a field of view about 50 arcmin square, and an energy resolution about 2 eV in the energy range of 0.3–1 keV. The TES microcalorimeter array provides the large field of view and good energy resolution at the same time. We plan to install an array comprising 16×16 pixels with an overall size of 1 cm square, which is cooled with a cryogen-free cooler. Pixels are readout by multiplexing signals using a multi-input SQUID amplifier, with each input connected to a TES microcalorimeter which is AC biased with a different frequency. We report the design and present status of the XSA system development.

Keywords: X-ray, microcalorimeter, transition edge sensor, TES, warm-hot intergalactic medium, WHIM, DIOS, XSA, SQUID, frequency domain multiplex, adiabatic demagnetization refrigerator, ADR

1. INTRODUCTION

Most of cosmic baryons predicted by the big-bang nucleosynthesis has escaped from direct detection, which is sometimes referred to as *missing* or *dark baryons*, and was first pointed out by Fukugita et. al. (1998).[1] Recent numerical simulations indicate that 30–50% of the total baryons at $z = 0$ is supposed to take a form of warm-hot intergalactic medium (WHIM) in the temperature range of 10^5–10^7 K.[2,3] The WHIM exhibits only weak observational signature, and its detection has been limited to the O_{VI} absorption features in bright QSO spectra at low redshifts ($z \lesssim 0.2$).[4,5] In this method, the observations are quite limited to particular line-of-sight towards QSOs, hence a possibility to identify emission line feature of the WHIM has been considered. It is shown that with an energy resolution of $\Delta E \sim 2$ eV we can distinguish the redshifted emission lines of O_{VII} (561 eV: 1s^2–1s2s, 568 eV: 1s^2–1s2p, 574 eV: 1s^2–1s2p, 665 eV: 1s^2–1s3p) and O_{VIII} (653 eV: 1s–2p) from other prominent Galactic lines and that a systematic survey observation of WHIM is feasible with a dedicated X-ray satellite mission.[6]

The Diffuse Intergalactic Oxygen Surveyor (DIOS) is a relatively small Japanese X-ray mission to study large-scale distribution of the WHIM using oxygen K emission lines. This kind of study is only made possible by superior energy resolution and large field of view (FoV). The combination of a Four-reflection X-ray Telescope, FXT, and a large array of superconducting transition-edge sensor (TES) microcalorimeters, XSA (X-ray Spectrometer Array), are the new technologies involved. The outline of the DIOS mission is described by Mitsuda et.

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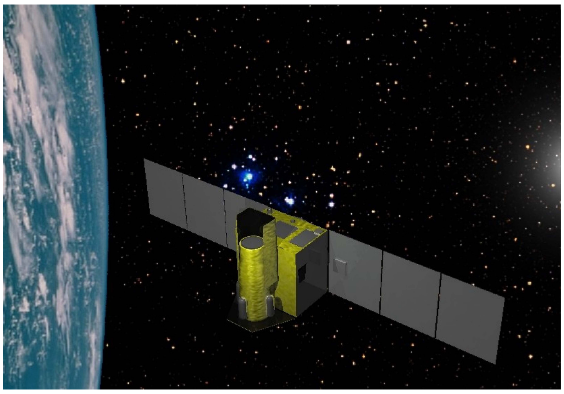

Figure 1. An illustration of the DIOS spacecraft in orbit. The height of the spacecraft is 1.5 m and the length of the solar paddle is 6 m.

Table 1. Parameters of the observing instruments onboard DIOS

Effective Area †	> 230 cm^2 (@ 0.6 keV, on-axis)
Field of View	$50' \times 50'$ (10 mm $\times$10 mm) ‡
$S\Omega$ †	> 100 cm^2 deg^2 (@ 0.6 keV)
Angular Resolution	$3'$ (0.6 mm; 16×16 pixels) ‡
Energy Resolution	2 eV (FWHM)
Energy Range	0.3 – 1 keV
Detection Efficiency	$> 50\%$ (@ 0.6 keV)
Power Consumption	280 W (XSA only)
Observing Life	> 5 yr

† Including the detection efficiency of the XSA, $> 50\%$.

‡ Assuming the focal length of the FXT, $L = 70$ cm.

al. (2004).[7] The design and performance estimation of the FXT is done by Tawara et. al. (2004a, 2004b).[8,9] In this manuscript, we describe the design of the XSA and the present status of the development. A larger Japanese X-ray mission named NeXT[10] (New X-ray Telescope mission) is also proposed to appear in 2010, which will have a similar instrument, SXS[11] (Soft X-ray Spectrometer). The DIOS XSA and the NeXT SXS hold many of their components in common, and the DIOS XSA provides a good chance for the performance verification of a TES microcalorimeter array in orbit for the first time.

The XSA consists of three major parts, the sensor, signal readout, and cryogenics. The sensor is a 16×16 pixel formated array of TES microcalorimeters, which utilize the sharp resistance change at a superconducting transition.[12,13] The thermometer sensitivity, $\alpha \equiv d\ln R/d\ln T$, is significantly increased by a factor of ~ 100 compared with a conventional ion-implanted thermistor, hence the energy resolution can be further improved. To date, $\Delta E_{\rm FWHM} \sim 4$ eV at 5.9 keV has been reported with single pixel TES microcalorimeters.[14,15] The change of current through the TES due to an incidence of an X-ray photon is read by a Superconducting Quantum Interference Device (SQUID) ammeter. By using a series SQUID array (SSA),[16] the signal can be amplified at low temperature with sufficiently low noise and wide bandwidth. This is a great merit because it enables us to multiplex signals at low temperature, which significantly reduces the heat input to the device leading to the realization of a large format array. In order to draw out the highest performance from microcalorimeters, the refrigeration system at the temperature as low as ~ 50 mK with sufficient cooling power and temperature stability of < 10 μK is required. Furthermore, the weight and electric power is limited for the small satellite, and the lifetime > 5 yr is requested. Development of such a cooling system is also challenging.

2. THE DIOS SPACECRAFT AND REQUIREMENTS OF THE XSA

An illustration of the DIOS spacecraft is shown in Fig. 1. The spacecraft will weigh about 400 kg, out of which the payload takes ~ 280 kg. The size before the launch is 1.5 m $\times$1.5 m $\times$1.2 m, and the 1.2 m side will be expanded to 6 m after the solar paddle deployment. This mass and the size enable the satellite to be launched as a piggy-back or sub-payload in H2 or Ariane rockets. It is also possible for a launch with the new ISAS/JAXA rocket, such as M-V light. The nominal orbit is a near earth circular one with an altitude of 550 km. The attitude will be 3-axis stabilized with momentum wheels, with typical pointing accuracy of $\sim 10''$. The direction of the FoV can be varied within $90^\circ \pm 20^\circ$ from the sun direction. With this constraint, any position in the sky can be accessed within half a year.

The major parameters of the observing instruments, FXT + XSA, are listed in Table 1. Basic concept of the FXT is a simple extension of two-stage conical optics used for high-throughput X-ray telescopes onboard ASCA[17] and Astro-E/E2.[18,19] Incident X-rays are reflected 4 times by thin-foil reflectors and are focused at only 70 cm from the mirror level. At the energy of oxygen lines (~ 0.6 keV), the reflectivity of the mirror surface is as high as 80% and the reduction of the effective area is not a serious problem. The four-stage reflection

(a) (b)

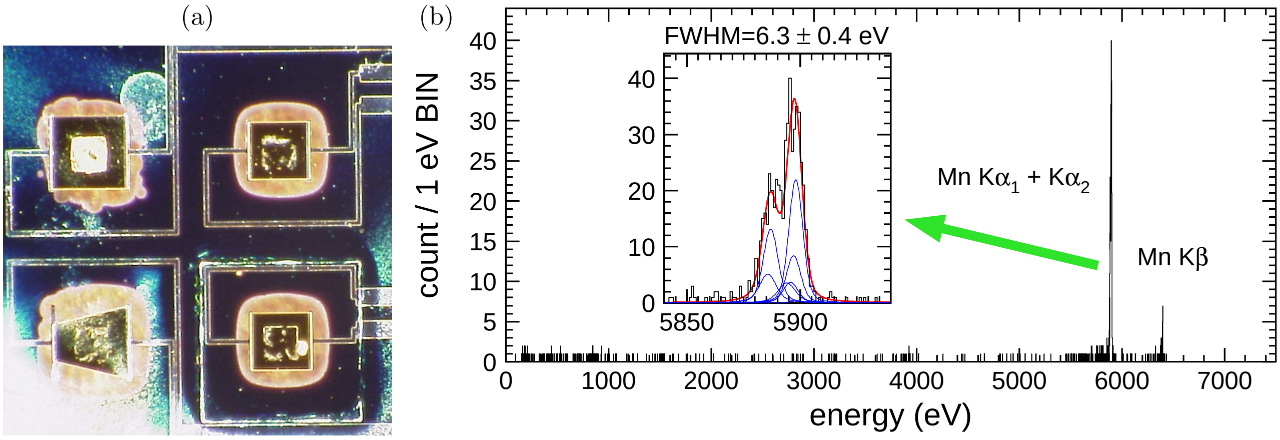

Figure 2. (a) A photograph of 2×2 array part of the 16 pixel TES microcalorimeter fabricated at Waseda University.[20,21] The size of the TES is 180 μm square for the bottom right pixel. (b) A pulse height spectrum of the Mn-Kα line from a ^{55}Fe isotope, obtained for the bottom right pixel in the photograph. The Kα_1 (5.89875 keV) and the Kα_2 (5.88765 keV) lines are starting to be separated. The energy resolution is fitted to be 6.3 ± 0.4 eV (FWHM),[22] if we consider the experimentally determined fine structure of the line shape including natural widths.[23]

gives a focal length half as long as the usual two-stage design, and substantially saves the volume and weight of the satellite. Moreover, a relatively small focal plane detector can have a wide FoV, which is a great advantage for a microcalorimeter array. In our base design, the outer diameter of the mirror, the effective area, and $S\Omega$ (integral of effective area in the XSA FoV) are 50 cm, 460 cm^2 (on-axis, FXT only), and 200 cm^2 deg^2 (FXT only, $50' \times 50'$ FoV), respectively, at 0.6 keV. Ray-tracing simulations indicate that the angular resolution is $2'$ (Half-Power Diameter), and the image quality does not show significant degradation at an offset angle of $30'$.[8,9]

To match with the FXT, the design values of the focal plane instrument XSA are determined. There will be 16×16 pixels with 0.6 mm square pixel size covering an area of about 1 cm square. The corresponding angular resolution and FoV are $3'$ and $50' \times 50'$, respectively. The energy range of the XSA will be 0.3–1 keV, in which the lower side is determined by the transmission of the blocking filters of the XSA and the higher side is by the FXT throughput. The detection efficiency of the XSA will be greater than 50% at 0.6 keV, including both the transmission of the blocking filters and the pixel gaps of the array. Another important feature of the XSA is the cryogen-free cooling system to ensure the observing life in orbit longer than five years. We are considering a serial connection of different types of coolers to achieve ~ 50 mK for the XSA within the available power budget of 280 W, which also includes the readout electronics. The XSA system is subject to a warm launch, therefore we have to allow for the initial cooling of the system for the first 1–3 months in the orbit.

3. THE SENSOR: TES MICROCALORIMETER ARRAY

We are developing a TES microcalorimeter array for the XSA in collaboration with SII NanoTechnology Inc., Waseda University, and Mitsubishi Heavy Industries. There are two types of devices that we are testing. One is a single pixel device fabricated at SII, for the purpose of studying the TES physics mainly to improve the energy resolution. It has a unique design with a bridge-shaped membrane,[24] and the characteristics of the device has been extensively examined.[25–28] The other is a device fabricated in most part at Waseda University, aiming mainly to establish the micromachining process for a large format array.[20,21] Both utilizes the Ti/Au bilayer TES with a normal state resistance ranging 40–120 mΩ. To date, energy resolution about 6 eV (FWHM) for 5.9 keV X-rays has been achieved for both types of devices.[22,25] Figure 2 shows an example for the latter device. The detection areas for both devices are still ~ 0.3 mm square, and it is necessary to enlarge the pixel size as well as to improve the energy resolution down to 2 eV.

As for the energy resolution, 2 eV resolution is within the reach considering the fact that the energy range

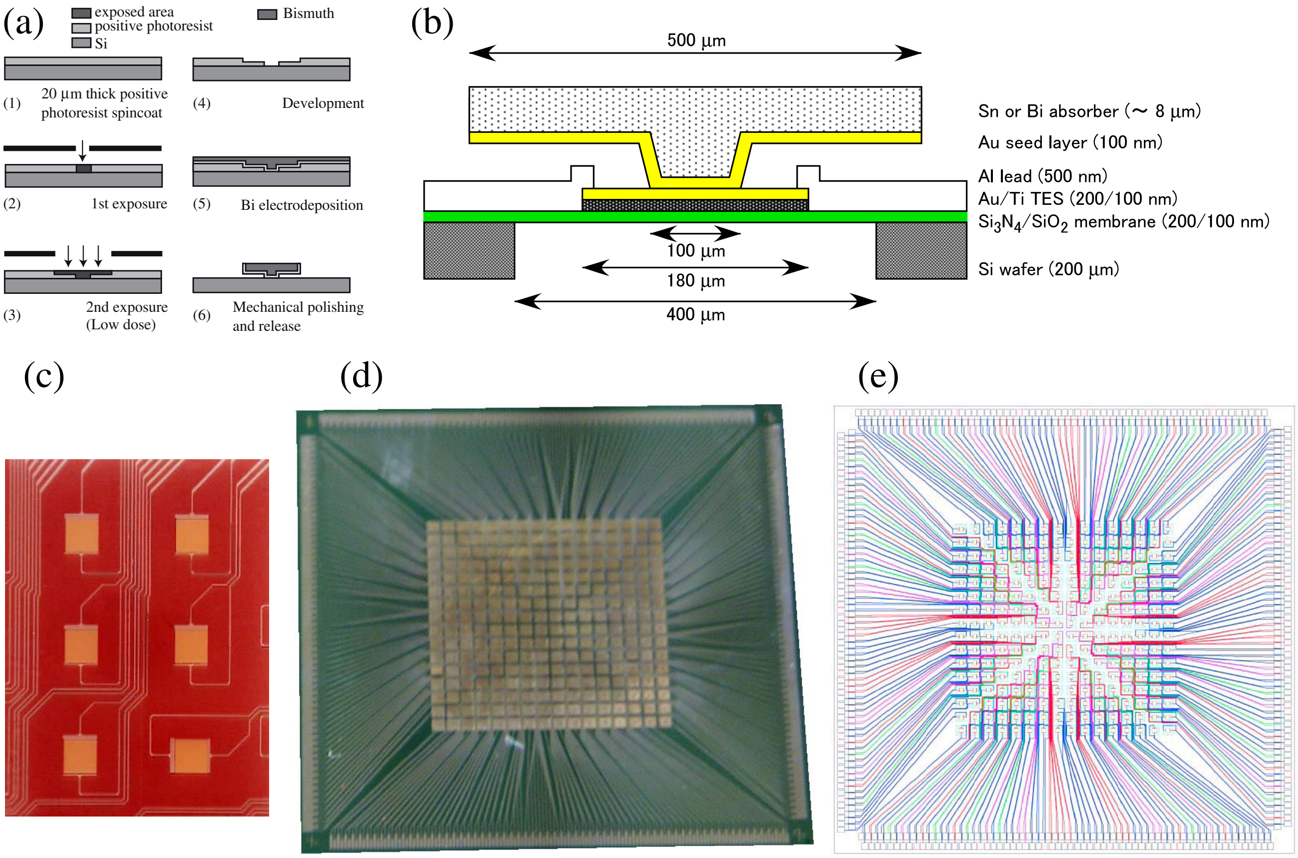

Figure 3. (a) A fabrication process of the Bi microabsorbers based on double exposing photoresist.[20] (b) A cross section of one pixel of the TES microcalorimeter array. (c) A photograph of the TES array before the absorber electrodeposition. (d) A prototype model of the 16 × 16 pixel TES microcalorimeter array with mushroom-shaped Bi absorbers. The TES and absorber are supported by a thin membrane of Si_3N_4 / SiO_2, and it is confirmed that this device works as microcalorimeters at the laboratory. (e) A photo mask for the aluminum wiring. Both width and pitch are 10 μm, and the size of the mask is 2 cm square.

for DIOS is limited below 1 keV. The theoretical energy resolution of a microcalorimeter is expressed as

$$\Delta E \simeq \sqrt{k_{\rm B}T^2C/\alpha} = \sqrt{TE_{\rm sat}}, \tag{1}$$

where k_B is the Boltzman constant, T is the operating temperature, C is the heat capacity of a detector, and $\alpha \equiv \frac{d\log R}{d\log T}$ is the sensitivity of a resistive thermometer which has resistance of R. It is therefore essential to make T lower, C smaller, and α higher for the improvement of the energy resolution. We do not need thick absorbers to stop soft X-rays below 1 keV, it is good to reduce the heat capacity C. Moreover, $E_{\rm sat} \equiv k_{\rm B}CT/\alpha$ represent the saturation energy for the TES device to warm up the detector until the superconducting thermometer getting completely normal sate. The formula indicates that the $\Delta E \propto \sqrt{E_{\rm sat}}$, hence scaling the $\Delta E = 6$ eV at 5.9 keV can accomplish 2 eV resolution at ~ 0.6 keV.

It is also strongly required to make a large format array (16 × 16 pixel, as the base design) covering ~ 1 cm square area with sufficiently high percentage ($\gtrsim 95\%$) of the aperture for the DIOS XSA. In order to fulfill this request, we are developing an electro-plating method to grow a metallic absorber supported by a thin stem on a TES, which is sometimes called as *mushroom-shaped* X-ray absorber. We have developed a unique fabrication method[20, 21] to realize such a mushroom-shaped X-ray micro-absorber as shown in Fig. 3a. A 20 μm thick photoresist is spincoated on a Si wafer with a Ti/Au TES array being patterned on a thin layers of Si_3N_4 and SiO_2. The photoresist is exposed twice using different photo masks and developed at once. The first exposure is a usual full exposure and the second exposure is a shallow exposure optimized for 10 μm depth. After the development, the Au seed layer for electrodeposition is evaporated, and thick layer of metal is electrodeposited on it. Mechanical polishing is then carried out to adjust the shape and finally the photoresist is removed using acetone. As a choice of the absorbing material, Sn, Bi, and Bi/Cu multilayer have been tested so far. The cross section of one pixel is shown in Fig. 3b.

We recently succeeded in making a prototype model of the 16×16 pixel TES microcalorimeter array with mushroom-shaped Bi absorbers as shown in Fig. 3c,d. The size of the absorber is 0.5 mm square and the gap is 0.1 mm, hence covering ~ 1 cm square region. Although the covering fraction of the aperture is not sufficiently high (64%), it is technically proven that we can make the pixel gap smaller down to ~ 10 μm. As shown in Fig. 3e, all the wiring are patterned on the front side surface of the Si wafer. Both width and pitch of the aluminum wiring are 10 μm, and the yield rate of the wiring to each pixel is nearly 100% for this device. The TES and absorber are supported by a thin membrane of Si_3N_4 / SiO_2, and it is confirmed that this device works as microcalorimeters at the laboratory. These results encourage us, while there are still several points to improve, such as quality and uniformity of the TES, weak adhesion of the absorbers, a long time constant component of the X-ray pulse which appears when we attach absorbers on the TES,[22] etc.

4. THE SIGNAL READOUT: FREQUENCY DOMAIN MULTIPLEX

We must readout signals from 256 pixels of TES microcalorimeters in the array for the DIOS XSA. The array and the front end electronics are located at the 100 mK and 1.8 K stage of the refrigerator, and it is increasingly difficult to connect all the signal and bias lines independently to the analog electronics at room temperature from the viewpoint of the thermal design. The practical number of channels is ~ 100 at the maximum. It is therefore indispensable to multiplex signals from several pixels at low temperature. The TES microcalorimeter is a low impedance device and signals are readout using SQUID (Superconducting Quantum Interference Device) as a change of the current through the TES. The advantage of the SQUID is that it has wide bandwidth compared with the X-ray signals from microcalorimeters, that it can realize sufficiently low noise at the whole usable frequency range, and that it works in principle at low temperature. Utilizing these characteristics, the signal multiplexing is being studied in several groups.[32–34] There are roughly two types of signal multiplexing, Time Division Multiplexing (TDM) and Frequency Domain Multiplexing (FDM). We are investigating the FDM technique based on the magnetic summation of the AC modulated signals using a multi-input SQUID amplifier.[31] SQUID is basically a device to detect small magnetic field (order of the fluxoid quantum $\Phi_0 = 2.07 \times 10^{-15}$ Wb) measuring a change of the Josephson voltage. The current through the TES is added and measured magnetically by coupling multiple input coils to one SQUID washer.

In Fig. 4, the basic concept of the FDM is presented.[29,30] An TES microcalorimeter is usually DC biased, while it is AC biased in the FDM scheme. By operating TES microcalorimeters with AC bias whose frequencies are high enough compared with $1/\tau_{\rm eff}$ of the thermal time constant of TES microcalorimeters, X-ray signals are amplitude modulated so that the signal band is shifted to the carrier frequency. Then, we can add signals from different pixels operated with different frequency without losing the signal information of individual pixels. In our base design, four signals are summed up using a 4-input SQUID amplifier and sent to the room temperature analog electronics (AE) using one pair of signal lines (hot, return). Figures 4b,c show a photograph of the first stage of the 4-input SQUID amplifier and the base design of the front end electronics (FEE) of the XSA located at the 100 mK or 1.8 K stage of the refrigerator. The signals are demodulated by either analog electronics like lock-in amplifier or digital filtering, and then evaluated for the pulse height using the optimal filter technique.[35] Table 2 summarizes the number of required wiring between the FEE and the AE.

We have so far achieved multiplexing two pixels using the 4-input SQUID amplifier[34] with a bridge circuit called Calorimeter Bridge Biased by an AC Generator (CABBAGE).[29,30] We are now working on the usual LCR circuit (Fig. 4c) and demonstrated 24 eV resolution with 42 kHz AC bias, which was 17 eV with DC bias. In order to realize the FDM, fast readout electronics (wide band, high slew rate, and large dynamic range) is needed, thus we are investigating the optimal parameters including SQUID and driving electronics, such as loop gain of the feedback circuit, input and mutual inductance of the SQUID, etc. We are also considering to increase the number of multiplex, and an 8-input SQUID amplifier is under development.

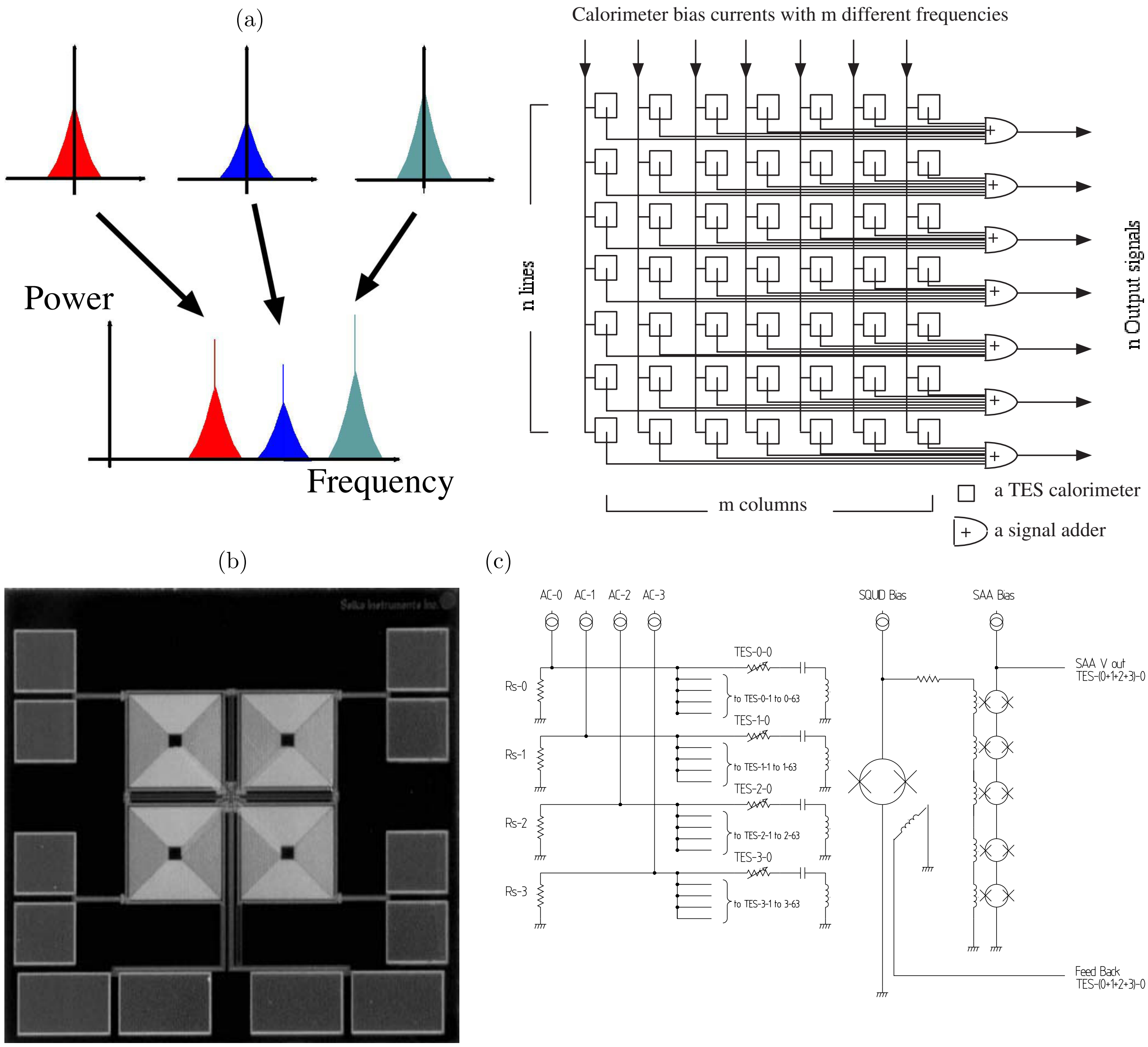

Figure 4. (a) The basic concept of the frequency domain multiplex.[29, 30] By operating TES microcalorimeters with AC bias whose frequency is high enough compared with the thermal time constant of the microcalorimeter, X-ray signals are amplitude modulated so that the signal band is shifted to the carrier frequency. Then, we can add signals from different pixels operated by different frequencies. When the $n \times m$ microcalorimeter array is operated by m of frequencies assigned at $\Delta f \sim 50$ kHz step, we can bind signals into n. The frequency band of $m \times \Delta f$ is required for each signal line. (b) A photograph of the first stage of a 4-input SQUID amplifier to add signals magnetically from different pixels.[31] (c) The base design of the front end electronics of the XSA located at the 100 mK or 1.8 K stage of the refrigerator.

Table 2. The estimation of required lines connecting from the cold stage to the analog electronics at room temperature.

Name	Contents	Number of lines
TES AC Bias	(hot,return) $\times$ frequency	2×4
SQUID Bias	(hot,return) $\times$ number of channels	2×64
SAA Bias	(hot,return) $\times$ number of channels	2×64
SQUID Feedback	(hot,return) $\times$ number of channels	2×64
TES Signal	(hot,return) $\times$ number of channels	2×64
Total		520

Table 3. List of coolers used for the refrigeration system of the DIOS XSA

Cooler	Purpose	Temperature	Specification	Cooling Power
ADR	coooling detector	50 mK	CPA 500 g, $B_{\max} = 0.8$ T	27 hours with 2 μW heat load
^{3}He sorption #1	cooling ADR at demagnetization phase	0.4 K	^{3}He gas 4.0 ℓ	30 min with 1.5 mW heat load
^{3}He sorption #2	cooling ADR shield at observation phase	0.4 K	^{3}He gas 1.2 ℓ	24 hours with 10 μW heat load
J-T cooler	recycling ^{3}He	1.8 K	^{3}He J-T cycle	10 mW @ 1.8 K
2-stage stirling #1	cooling J-T cooler	20 K, 100 K		200 mW @ 20 K
2-stage stirling #2	cooling IVCS, OVCS	20 K, 100 K		200 mW @ 20 K

5. THE CRYOGENICS: CRYOGEN-FREE ADR

The goal of the mission life of DIOS in orbit is > 5 yr. In order to accomplish this with a small satellite, it is essential to introduce mechanical coolers down to the starting temperature of the Adiabatic Demagnetization Refrigerator (ADR). We need as low as 50 mK temperature for the cold stage to operate the TES microcalorimeter array, and such low temperature is only available with ADR in the zero gravity environment. Difficulty in adopting a mechanical cooler in combination with ADR is that ADR usually ejects much of heat output during the demagnetization phase, which is required, e.g., once a day. The design of the refrigeration system depends much on the starting temperature of the demagnetization and how to compromise with this temporal heat output. In our base design, we decided to set the starting temperature down to 0.4 K by introducing two sets of ^{3}He sorption refrigerators. The low starting temperature allows us to make use of smaller magnet current and smaller paramagnetic salt, thus smaller heat output. Furthermore, one side of the ^{3}He sorption refrigerator is completely dedicated to undertake the heat output during the demagnetization phase, and the evaporated ^{3}He is recycled to liquid during the observation phase. The other side takes care of the gradual heat load during the observation phase.

Figure 5 represents a block diagram of the refrigeration system of the DIOS XSA, and Table 3 shows a list of the coolers used in the diagram. To achieve temperature below 50 mK, we will use Chromium Potassium Alum (CPA; $CrK(SO_4)_2 \cdot 12H_2O$) as a paramagnetic salt of the ADR, instead of Ferric Ammonium Alum (FAA; $Fe_2(SO_4)_3(NH_4)_4 \cdot 24H_2O$) which is used for the Astro-E/E2 XRS.[36, 37] The starting temperature 0.4 K of the ADR is determined by the ^{3}He sorption refrigerator #1, which repeat a closed cycle of condensation of liquid ^{3}He and evacuation to the sorption pump. This absorbs the heat during the demagnetization of the ADR, and recycles ^{3}He during the observation. Another ^{3}He sorption refrigerator #2 cools the ADR shield during the observation and recycles during the demagnetization. The ^{3}He sorption refrigerator itself is commonly used for ground experiments and there have been several applications in space. Besides the refrigerator, we also need heat switches between the cooler and the 0.4 K stage, and between 1.8 K. For the purpose of recycling ^{3}He, we adopt a J-T cooler utilizing ^{3}He Joule-Thomson cycle at the cooling side temperature of 1.8 K. J-T coolers are being developed in Japan for the SMILES and SPICA missions,[38, 39] and sufficient cooling power at 1.7 K has been demonstrated. There are also two sets of 2-stage stirling coolers #1 and #2, which take care of the outermost part of the refrigeration system. Both have 20 K and 100 K stages with 200 mW cooling power at 20 K. One is used for cooling the J-T cooler and the other is for cooling IVCS (Inner Vacuum Cold Shield; 20 K) and OVCS (Outer Vacuum Cold Shield; 100 K). The Astro-F satellite is equipped with a 2-stage stirling cooler and the performance and life of the cooler have been extensively tested on ground.[40]

Since the ADR is a key portion of the system, we made an engineering model in collaboration with Sumitomo Heavy Industries to study and demonstrate major components of the ADR, i.e., the CPA salt, the helium gas gap

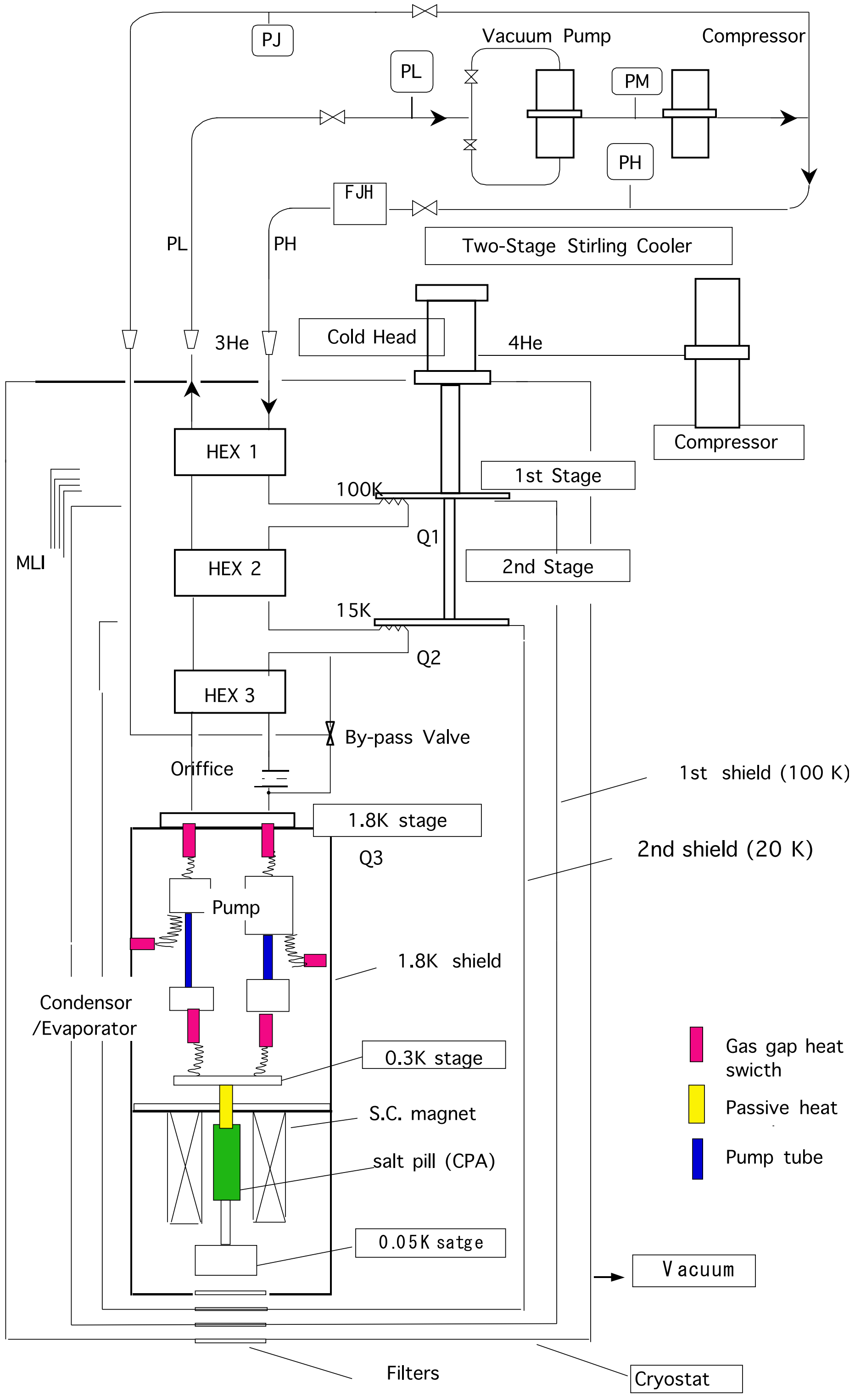

Figure 5. A block diagram of the refrigeration system of the DIOS XSA. The 1st (OVCS; 100 K) and the 2nd (IVCS; 20 K) shields are cooled by another 2-stage stirling cooler.

heat switch, and the superconducting magnet. The CPA salt of 750 g is made by the recrystallization method and thermal conductivity inside the crystal is increased by 4500 lines of 0.3 mmϕ Cu. We chose 1.7 K for the starting temperature of the ADR for the engineering model, and the heat switch worked fine at this temperature. Small amount of liquid helium as coolant is used to make 1.7 K, and the vacuum shield of the helium tank is cooled by a Gifford McMahon (GM) cryocooler. The superconducting magnet with $B_{\rm max} = 2$ T at 8 A coil current is cooled to 2 K only by conduction considering the cryogen free system. Both TES and SQUID make use of the superconductivity, the magnetic shielding is also crucial. We set up three cancel magnet to reduce the magnet field at the detector stage, and magnetically shielded the devices with Nb and Cryoperm. We have tested the base temperature, holding time, and the temperature stability with the engineering model, and confirmed that they are almost as we expected. Several types of TES microcalorimeters and SQUID have been installed in this system, and their performance tests are ongoing.

6. SUMMARY AND FUTURE PROSPECTS

The development of the DIOS XSA is in progress. The XSA system has a similar design to the NeXT SXS, and will be the first TES microcalorimeter array working in orbit. It consists of three major parts, the sensor, signal readout, and cryogenics. The 16×16 pixel TES microcalorimeter array with pixel size of 0.6 mm square covering ~ 1 cm^2 ($\sim 50' \times 50'$ assuming the FXT focal length of 70 cm) and energy resolution of 2 eV (@ 0.3–1 keV range) is intended for the sensor. So far, ~ 6 eV (@ 5.9 keV) resolution for two types of single pixel TES microcalorimeters has been achieved, and a prototype model of the 16×16 pixel array with mushroom-shaped Bi absorbers has been fabricated recently. The Frequency Domain Multiplexing (FDM) will be used to readout signals from each pixel in the array combining them into 64 channels or less. The 4-input SQUID amplifier is used to bind signals, which has been fabricated and tested for AC readout. As for the cryogenics, the cryogen free ADR with the series connection of two sets of ^{3}He sorption refrigerators, one J-T cooler, and two sets of 2-stage stirling cooler is considered. We have made the engineering model to test mainly the ADR part of the refrigeration system. As a part of the cryogenics, it is also important to establish the blocking filters which have good transmission ($> 50\%$) for ~ 600 eV X-rays. We are also considering the international collaborations, and hope to launch the DIOS satellite until ~ 2010 before the NeXT mission.

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