Development of 1.5 THz Cartridge-type Multi-pixel Receiver Based on HEB Mixers

Yen-Ru Huang*, Chuang-Ping Chiu, Hsian-Hong Chang, Yen-Yu Chiang, and Ming-Jye Wang
Institute of Astronomy and Astrophysics, Academia Sinica, Taipei 10617, Taiwan
*Contact: yenruhuang@asiaa.sinica.edu.tw, phone: +886-2-2366-5309

Abstract— **A design of 2 × 2 NbN-based hot-electron-bolometer (HEB) mixer array receiver cartridge has been demonstrated here by using multiple local oscillator (LO) beams. In our design, the 1.5 THz LO beam is split into four uniform sub-beams with a spacing of 18 mm by using a power distributor, then arrives at a four-pixel silicon lens with twin slot antenna (TSA) through a large-area beam splitter. An additional four-pixel HDPE lens is located at 120 mm in front of the silicon lens to increase the size of beam waist for fitting to the aperture parameter of sub-reflector of GLT. Some cryogenic tests of cartridge have been carried out. In this article, we report the design, assembly, thermal analysis, and some testing results of cartridge.**

INTRODUCTION

The superconducting NbN based hot-electron-bolometer (HEB) mixer is one of the commonest detectors for THz radio astronomy due to its near quantum limit noise performance and low local oscillator (LO) power requirement [1], and has already been applied in several astronomical observatories [2-4]. In the past years, we have successfully realized 1.4 THz NbN based HEB mixers with a receiver noise temperature of around 2000K and a bandwidth of 3.5 GHz. The receiver noise temperature can be further improved by replacing a silicon lens with anti-reflection coating. In addition, for astronomy receivers, multi-pixel receiver is more favourable because of high mapping speed. However, uniformly injecting enough LO power to each pixel is a critical issue in a THz multi-pixel receiver. To achieve the minimum power loss and uniform beam profiles, most HEB array receivers apply the polarizing beam splitters for the LO beams [5,6], including Fourier phase gratings, wire-grid polarizers, multilayer structures, etc. In our design, simple dielectric slab beam splitters are used which can suppress the variations of transmittance and reflectance below 2.2% in the frequency range from 1.45 THz to 1.55 THz.

The receiver cartridges for the Atacama Large Millimeter /submillimeter Array (ALMA) have many advantages, including high cooling efficiency and good modularity which can simplify the efforts on telescope site. In this paper, we report the designs of single-pixel and 2×2 HEB mixer array ALMA-type cartridge receiver at the frequency range of 1.45 - 1.55 THz. The pixel number in our design can be further extended to 9 based on currently available LO power. We target to deploy this multi-pixel THz receiver cartridge on the Greenland Telescope (GLT) [7]. An engineering model of cartridge which can be used for single-pixel and 2×2 array receiver has been constructed. The thermal analysis, cooling test of cartridge, and LO source performance will be discussed.

CARTRIDGE DESIGN CONCEPT

The receiver cartridge comprises three cooled stages with operation temperatures of 4K, 15K, and 110K. To boost output power, cooled frequency multipliers are used in the LO module which is provided by VDI Inc. The fundamental frequency of LO signal is generated by a synthesizer and multiplied to Q-band frequency. Then the power is amplified and fed through the vacuum-type waveguide feedthrough (WR22) at 300K base-plate to reduce power losses. The frequency is further multiplied by a cooled two-doubler module and a cooled two-tripler module to reach the target frequency. The output horn of LO module is fixed at the focal point of a 90 degree off-axis parabolic mirror on the 110K plate with an effective focal length of 30 mm to make the Rayleigh length enough. For 2×2 array receiver, a power distributor module is used to divide the LO beam into four sub-beams with a spacing of 18 mm. After that the LO and radio frequency (RF) beams are combined by a large-area beam splitter made of mylar films with 13 μm thickness, and then couple to the HEB mixer adhered on the backside of a silicon lens. The reflectance of mylar beam splitter is about 20%. In addition, another four-pixel HDPE lens is located at 120 mm in front of the silicon lens to increase the size of beam waist for matching the aperture parameter of the sub-reflector of the GLT antenna.

The design and assembly of the engineering model cartridge had been completed, and the testing of single-pixel design has been carried out first to check the performance. Fig. 1 is the schematic diagram of the single-pixel and four-pixel receiver cartridge design. In these two engineering models, the arrangements of cartridge are identical, except of the mixer block, the LO coupling module, and the number of IF channels. Fig. 2(a) shows the four-pixel power distributor module which consists of TE and TM mode polarizing beam splitters made of quartz and silicon slabs respectively due to the polarization direction of LO signals. To achieve uniform distribution patterns of the output sub-beams, the thicknesses of the quartz and silicon slabs are optimized to 135.5 μm and 130.5 μm respectively which are depicted in Fig. 2(b).

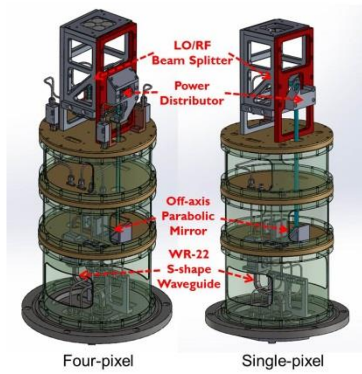

Fig. 1 The schematic diagram of the single-pixel and four-pixel cartridge design.

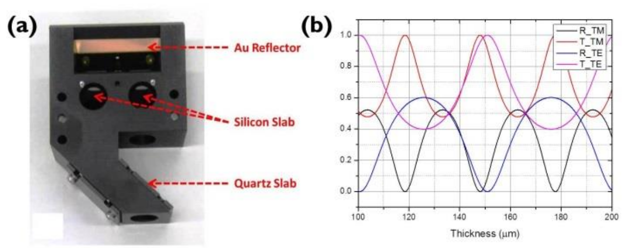

Fig. 2 (a) The four-pixel power distributor module. (b) The calculated transmittance and reflectance of polarizing beam splitters versus thickness.

Cooling Test of Cartridge

The vacuum and cooling test of cartridge has been completed. The loading system with an ALMA-type testing cryostat is shown in Fig. 3. There are two parallel slippery tracks and a transportation plate on the system, and the cartridge can be adjusted to the target height by using a hand pulled stacker. The cartridge is mounted on the under-side of transportation plate, and then be slowly loaded into the testing cryostat along the slippery tracks. The Sumitomo RDK-3ST three stage cryocooler is used, which has cooling powers of 1.0 W at 4.4K for the 4K stage, 8 W at 18K for the 15K stage, and 33 W at 85K for the 110K stage.

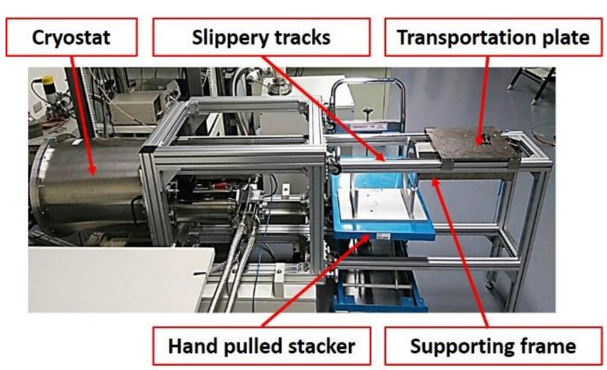

Fig. 3 The loading system and testing cryostat for cartridge.

The vacuum sealing test of 300K base-plate shows a helium leakage rate below 2.4E-6 mbar*L/s within 2000 seconds which can meet the ALMA specification, and the vacuum level of 5.7E-5 mbar at room temperature can be achieved. The temperatures of three stages during cooling procedure are shown in Fig. 4. The dashed line is the result of bare cartridge body, and the solid line is that of the engineering model cartridge. The balanced temperatures of three stages are 2.8K, 14.8K, and 79.5K for the bare cartridge, and 2.8K, 15.3K, and 80.2K for the single-pixel engineering model cartridge respectively. The DC biases for cooled multipliers of the LO module are applied before cooling. The slightly increase of temperature at 15K and 110K stages is due to extra thermal loading, such as cables, wires, and waveguides which are not included in the bare cartridge body.

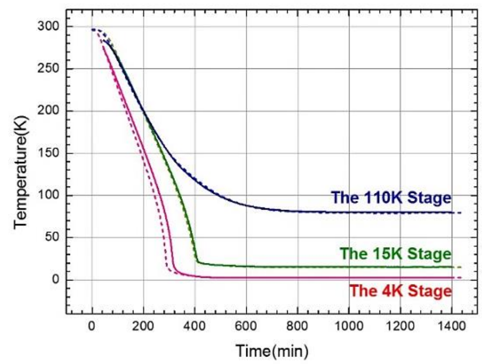

Fig. 4 The temperatures of the three cooled stages versus time during cooling procedure. The dashed line is the result of the bare cartridge, and the solid line is that of the engineering model cartridge.

To understand the thermal loading after the synthesizer of LO module is turned on, we mounted more sensors on different positions to measure the temperature variation. Fig. 5 shows the temperature evolution of each sensor when synthesizer of LO module is turned on and off. The two-doubler module is heated from 108.8K to 152.1K as the amplified Q-band LO signals are turned on, and the temperature of two-tripler module increases about 10K. However, the 4K plate and the mixer block (~ 3.4K) have a temperature increase below 0.015K. We expect that the performance HEB mixer won’t be affected during operation.

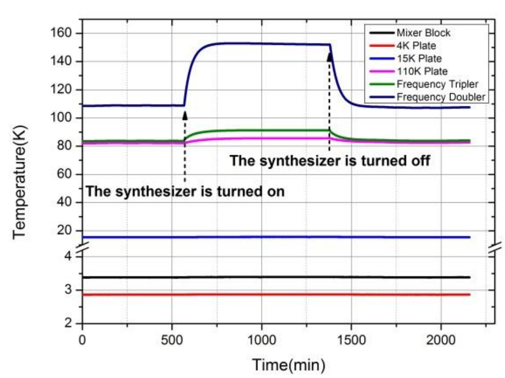

Fig. 5 The temperature distribution of the cold cartridge.

THERMAL ANALYSIS

The temperature distribution of cartridge has been simulated by ANSYS. The three cooled plates have a thickness of 10 mm and diameters of 169.0 mm at the 4K stage, 169.5 mm at the 15K stage, and 170.0 mm at the 110K stage respectively. The 4K and 15K plates are made of oxygen-free copper (OFCu) with gold plated, but the 110K plate is made of aluminum (Al). The thermal conductances of the three stages are set to 1.7 W/K, 5.6 W/K [8], and 7.0 W/K, and the heat generation of each frequency doubler of LO module are set to 0.75 W and 2.2 W when the synthesizer is turned off and on respectively. Fig. 6(a) shows the simulated temperature distribution of the bare cartridge, and Fig. 6(b) and 6(c) are that of the engineering model cartridge when the synthesizer of LO module is turned off and on respectively. The simulated balanced temperatures of the 110K plate, the two-tripler module, and the two-doubler module are 81.1K, 84.0K, and 105.2K when the synthesizer is off, and 83.3K, 91.0K, and 152.8K respectively when the synthesizer is turned on, which are consistent with our measurement results.

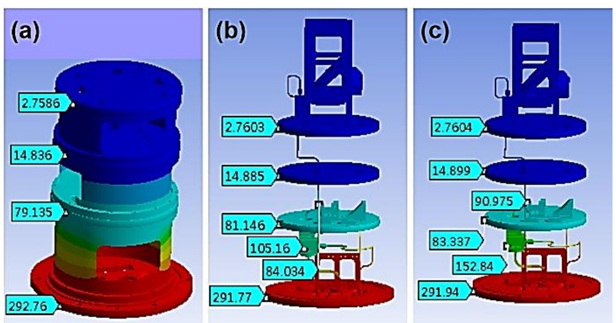

Fig. 6 (a) The simulated temperature distribution of the bare cartridge. (b) The simulated temperature distribution when the synthesizer is turned off. (c) The simulated temperature distribution when the synthesizer is turned on.

THE OUTPUT POWER OF THE LO MODULE

Cooled frequency multipliers are used in the LO module to boost the output power at the frequency range of 1.45 - 1.55 THz. The LO output power as the multipliers cooled/not cooled has been measured, as shown in Fig. 7. The LO output power with cooled multipliers is about 2.5 times higher than that at room temperature. The measurement result is much higher than the estimated value (about 40% enhancement when the two-tripler module is cooled only). The higher output power at low temperature is attributed to a higher conversion gain of the two-doubler module at low temperature, similar phenomenon to the cooled tripler. Such LO power boost could provide us more margins on our 9- or more pixels receiver in the future.

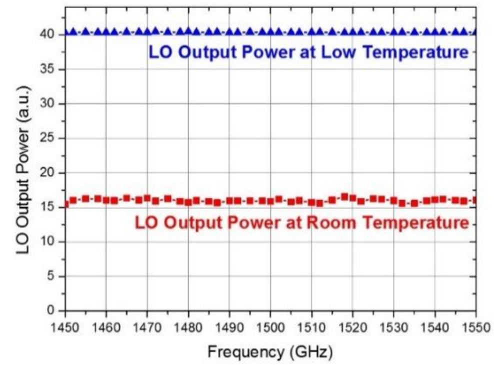

Fig. 7 The LO output power measurement at room temperature and low temperature.

SUMMARY

We present the design of engineering model of 1.5 THz single/four -pixel cartridge-type receiver based on HEB mixers. The cooling test of single-pixel cartridge has been carried out, and the measured temperature distribution of the cold cartridge is consistent with the simulation result. Mechanical analysis of cartridge will be done soon. The output power of the LO module at low temperature is nearly twice higher than the predicted value, which can provide more margins for 9- or more pixels receiver in the future. Testing with HEB mixers will be the next milestone to evaluate the performance of the cartridge receiver.

REFERENCES

F. Rodriguez-Morales, K. S. Yngvesson, E. Gerecht, N. Wadefalk, J. Nicholson, et al. "A terahertz focal plane array using HEB superconducting mixers and MMIC IF amplifiers," *IEEE Microw. Wireless Compon.*, vol. 15, pp. 199-201, Apr. 2005.

C. Risacher, R. Guesten, J. Stutzki, H. Huebers, D. Buechel, et al. “First supra-THz heterodyne array receivers for astronomy with the SOFIA observatory,” *IEEE Trans. Terahertz Sci. Technol*., vol. 6, pp. 199-211, Mar. 2016.

S. Cherednichenko, V. Drakinskiy, T. Berg, P. Khosropanah, and E. Kollberg, “Hot-electron bolometer terahertz mixers for the Herschel Space Observatory,” *Rev. Sci. Instrum.*, vol. 79, 034501, Mar. 2008.

C. Walker, C. Kulesa, P. Bernasconi, H. Eaton, N. Rolander, et al. “The Stratospheric THz Observatory (STO),” *Proc. SPIE*, vol. 7733, 77330N, July 2010.

Y. C. Luo, X. X. Liu, D. J. Hayton, L. Wei, J. R. Gao, and C. Groppi, “Fourier phase grating for THz multi-beam local oscillators.” in *ISSTT 2015: Proceedings of the 26th International Symposium on Space Terahertz Technology*, 2015, paper T2-4.

U. U. Graf and S. Heyminck, “Fourier gratings as submillimeter beam splitters,” *IEEE Trans. Antennas Propag.*, vol. 49, pp. 542-546, Apr. 2001.

H. Hirashita, P. M. Koch, S. Matsushita, S. Takakuwa, M. Nakamura, et al. “First-generation science cases for ground-based terahertz telescopes,” *Publ. Astron. Soc. Jpn.*, vol. 68, R1, Feb. 2016.

M. Sugimoto, Y. Sekimoto, S. Yokogawa, T. Okuda, T. Kamba, et al. “Thermal link for cartridge-type cryostat,” *Cryogenics*, vol. 43, pp. 435-439, Mar. 2003.