A Cartridge-type Multi-pixel Receiver for the 1.5 THz Frequency Band of GLT

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Abstract—A prototype of 2 × 2 NbN hot electron bolometer (HEB) mixer array receiver, operating at 1.5 THz, has been designed and demonstrated for the Greenland Telescope (GLT). In this design, the LO beam splits into four equal-power sub-beams with a spacing of 18 mm by a power distributor module, then these sub-beams arrives at a four-pixel silicon lens array and are coupled by the twin slot antenna (TSA) of HEB mixer through a large-area beam splitter made of a Mylar film with 13 μm thickness. An additional HDPE lens is located at 120 mm in front of the individual silicon lens to increase the size of beam waist for fitting to the aperture parameter of GLT sub-reflector, thus this design can match the optical parameters between Si/TSA and GLT antenna. The pixel number can be further extended to 9 based on the high output power of LO module.

INTRODUCTION

The National Science Foundation (NSF) in the United States awarded the 12-m ALMA-NA Vertex Prototype Telescope to a team, led by the ASIAA, in 2011 to deploy the telescope on the summit of Greenland ice sheet, named as Greenland Telescope (GLT), for pursuing Submillimeter Very Long Baseline Interferometry (submm-VLBI) observations on the northern sky [1, 2]. Besides, due to the excellent weather conditions, the GLT could be also applied for single dish observations up to 1.5 THz window. The major advantage of GLT operating at THz frequencies is the higher angular resolution, as compared to space or airborne THz telescopes. Thus, high resolution and high speed mapping will be the important subjects for GLT.

Multi-pixel array receiver is more preferred for enhancing the mapping speed of telescope [3, 4]. In recent years, we devoted on developing a 1.5 THz multi-pixel cartridge receiver based on hot-electron-bolometer (HEB) mixers for GLT [5, 6]. The ALMA-type receiver cartridge was chosen in our design, which has many advantages, such as high cooling efficiency and good modularity. The local oscillator (LO) source in our receiver cartridge can provide an output power of 14 μW at 1.5 THz, and up to 35 μW while the frequency multipliers are cooled. The boosted LO power can further extend the pixel number to 9 in the future.

PERFORMANCE TESTING OF THE RECEIVER CARTRIDGE

The engineering model of 1.5 THz 2 × 2 HEB mixer array receiver cartridge has been designed and assembled basically, and we tested the single-pixel configuration first to check the performance of cartridge. The single and four pixel configurations are identical, except of the power distributor module and the mixer block.

In our cartridge design, the quasi-optical path mainly comprises two parts: the LO beam path and the radio frequency (RF) beam path. For the LO beam path, the amplified Q-band frequency signal is fed through the 300 K base-plate to reduce power losses, and then passes through the cryogenic two-doubler module and two-tripler module to get the LO frequency at 1.5 THz. The horn of the LO module and a 90 degree off-axis parabolic mirror with an effective focal length of 30 mm are mounted on the 85 K plate to make the Rayleigh length long enough. Then the LO beam is divided into four sub-beams with a spacing of 18 mm through the power distributor module which consists of TE and TM mode polarizing beam splitters made of quartz and silicon slabs respectively. After that the LO sub-beams and RF beams are combined by a large-area beam splitter made of 13 μm Mylar film, and then coupled by a four-pixel silicon lens module with the twin-slot antenna (TSA) of individual HEB mixer chip. The calculated transmittance of the Mylar beam splitter is about 80%. For the RF beam path, an additional four-pixel HDPE lens model is located at 120 mm in front of the silicon lens to increase the beam waist size for matching with the aperture parameter of GLT sub-reflector.

After the engineering model assembled, the LO output power measurement was carried out through the single-pixel power distributor by using the bolometer from QMC instrument. The single-pixel power distributor module simply consists of two reflectors to align the LO signal to HEB mixer. It is noticed that the Mylar beam splitter on 4 K stage was mounted perpendicularly to the original attitude for guiding the signals to outside. A large-area 90 degree off-axis parabolic mirror was placed in front of the vacuum window to focus LO signals into the bolometer. An optical chopper and a lock-in amplifier were applied here to measure the modulated output peak-to-peak voltage. The measurement result is shown in Fig. 1, where the red curve is the output amplitudes at room temperature. The variation of voltage (or output power) with frequency perfectly meets the specifications provided by VDI. The black curve is the output amplitude of power detector as the frequency two-doubler and two-tripler modules cooled, which is about 2.5 times higher than that at room temperature.

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The LO beam profile is shown in Fig. 2, which is measured by the same setup but with an additional 2-mm pinhole mounted on an x-y linear motorized stage to define the measurement pixel on the scanning frame. The profile of beam pattern is close to the Gaussian function with negligible distortion, and the full width at half maximum (FWHM) is about 4.479 mm.

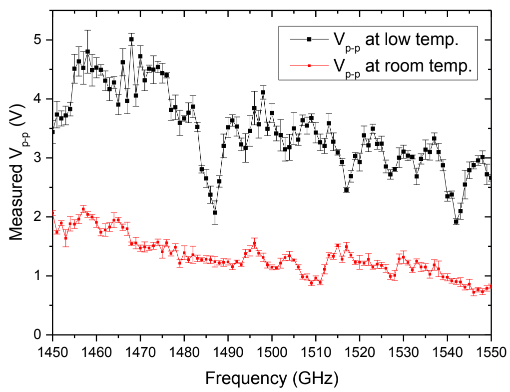

Fig. 1 The output power measurement of 1.5 THz LO module at room and low temperatures.

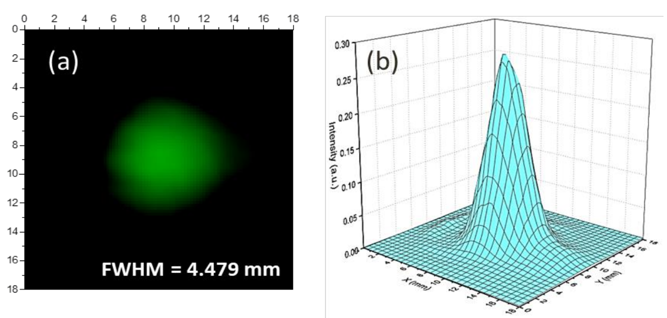

Fig. 2 The beam profile of LO module.

THE TEMPERATURE OF COLD CARTRIDGE

The Sumitomo RDK-3ST three-stage cryocooler is applied in our testing cryostat, which has cooling powers of 1.0 W at 4.4 K for the 4 K stage, 8 W at 18 K for the 15 K stage, and 33 W at 85 K for the 85 K stage. The cooling test had been carried out and the result shows that the balanced temperature is 3.2 K, 15.8 K, and 83.5 K on the three temperature stages of cartridge respectively. The DC biases for cooled two-doubler module of the LO system were applied before cooling. On the other hand, in order to understand the thermal loading as the LO system works normally (synthesizer of LO module turned on and the LO signal amplified), we mounted six sensors on different positions to measure the temperature distribution. As LO system working, the two-doubler module is heated from 95.3 K to 108.1 K and the temperature of two-tripler module increases about 3.2 K. However, the 4K plate and the mixer block (~ 3.6 K) only have a temperature increase less than 10 mK.

Fig. 3 shows the temperature variation at mixer block with a resolution of 0.2 second while the LO system was turned on. The temperature variation is just 8 mK within 17.5 hours and therefore we can expect that the HEB mixer performance won't be affected during whole system in operation.

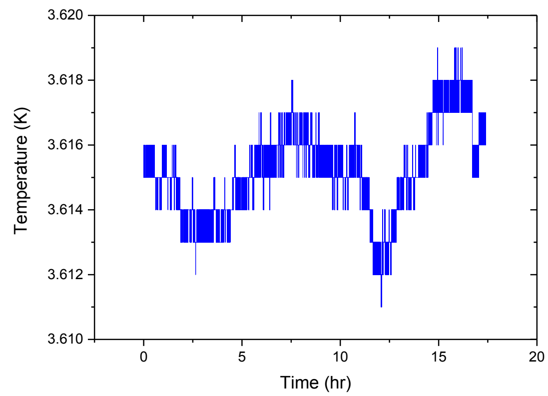

Fig. 3 The temperature stability of mixer block.

RF PERFORMANCE TESTING OF HEB MIXERS

The RF performance of single-pixel receiver cartridge with HEB mixer was tested. The HEB mixer is made of NbN film with a thickness of 17 nm, and the 1.5 THz twin-slot antenna was applied here [6]. To match the characteristic impedance of the lumped port in the antenna design, the gap length and micro-bridge width were defined to 0.55 μm and 1.57 μm respectively. The DC testing results of HEB mixer shows that the critical temperature (T_C) and normal-state resistance (R_n) is about 10.4 K and 61 Ohm respectively. For the RF performance test, the user controlled attenuation (UCA) port in the LO module was used for optimizing the LO power. It is noted that there is no stabilization mechanism of LO pumping power presently. The current-voltage (I-V) characteristics of HEB mixer was measured under various LO pumping levels, as shown in Fig. 4(a). The optimal pumped situation, with UVA bias voltage of 1.55 V, was chosen for receiver noise temperature (T_{rec}) measurement. The intermediate frequency (IF) power under hot/cold load and the T_{rec} of cartridge receiver are indicated in Fig. 4(b). The T_{rec} is about 2200 K as the HEB is biased at 0.3 mV. The test result is quite convincing which is similar to that tested in wet dewar before. It should be noted that the Si lens has no anti-reflection (AR) coating. The performance of cartridge receiver could be further improved by using Si lens with AR coating and a better HEB mixer.

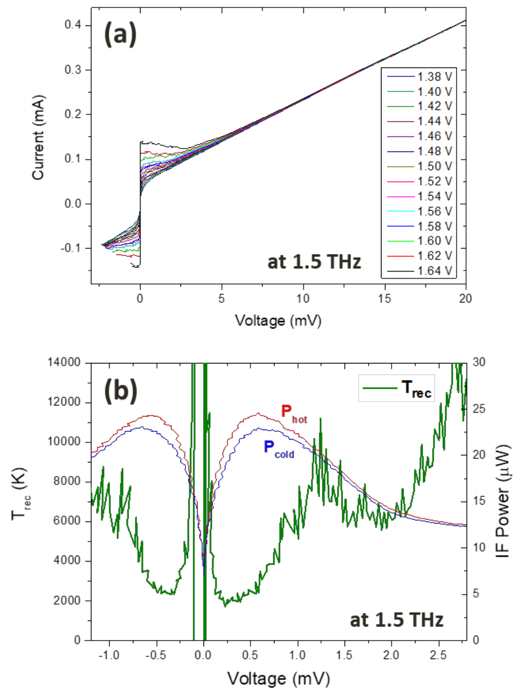

Fig. 4 (a) The I-V curves with different LO pumping power. (b) The result of hot-cold load measurement.

SUMMARY

We have successfully designed and assembled an engineering model of 1.5 THz single/four -pixel cartridge-type receiver based on HEB mixers. At present, the performance testing of single-pixel design has been completed, including the vacuum and cooling test, the output power and beam profile of LO source, and receiver noise measurement. From our results, the LO output power is large enough for applying more pixels in the future and the temperature variation of mixer block is quite small (~ 8 mK) within a long monitoring period. In addition, the RF performance testing of HEB mixers has also been carried out, and the optimal pumped situation can be achieved. In the future, we will deploy HEB mixers with better performance on the cartridge and characterize the four-pixel cartridge receiver cartridge.

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