A 4.7 THz HEB QCL Receiver for STO2

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Abstract— **We report on a 4.7 THz heterodyne receiver designed for high resolution spectroscopy of the astronomically important neutral oxygen (OI) line at 4.745 THz. The receiver is based around a hot electron bolometer (HEB) mixer and quantum cascade laser (QCL) local oscillator. This receiver has been developed to fly on the Stratospheric Terahertz Observatory (STO-2), a balloon-borne 0.8 m telescope observing from an altitude of 44 km for 14 days or more. We measure a double sideband receiver noise temperature of 815 K (~ 7 times quantum noise) with a noise temperature IF bandwidth of 3.5 GHz. We describe the receiver performance expected in flight and outline novel approaches to QCL amplitude and frequency stabilization.**

INTRODUCTION

The fine structure line of neutral oxygen (OI) at 4.7448 THz offers astronomers a valuable tool with which to study the lifecycle of star forming regions within giant molecular clouds in the Milky Way. Large scale surveys with extremely high spectral resolution and sensitivity are required to determine large scale kinematics within these clouds prompting the development of a super-THz heterodyne receiver near this frequency. Due to strong water absorption in the atmosphere, it is not possible to observe the OI line from Earth. Therefore, this receiver requires a compact high powered local oscillator (LO) that can be operated in fight from an aircraft or higher.

We report on a 4.7 THz heterodyne receiver designed specifically for high resolution spectroscopy of the OI line. This receiver has been developed to fly on the 2016 flight of the Stratospheric Terahertz Observatory (STO-2) balloon craft. Following from STO [1], the STO-2 platform consists of a balloon-borne observatory operating a 0.8 m diameter telescope at an altitude of > 40 km for 14 days or more. Heterodyne receivers are used to detect the brightest of the fine structure lines, namely those of, ionized nitrogen [NII] at 1.4 THz, ionized carbon [CII] at 1.9 THz, and neutral oxygen [OI] at 4.7 THz.

STO-2 is primarily aimed at improving understanding of the life cycle of stars in our Galaxy by observation of interstellar clouds and star forming regions and by attempting to further understand the relationship between star formation and the life cycle of interstellar clouds. STO-2 proposes to specifically address the following points:

1. Determine the life cycle of Galactic interstellar gas.
2. Study the creation and disruption of star-forming clouds in the Galaxy.
3. Determine the parameters that affect the star formation rate in a galaxy.
4. Provide templates for star formation and stellar/interstellar feedback in other galaxies.

STO-2 will make 3-dimentional maps of the dynamics, structure, energy balance, turbulence and pressure of the Milky Way’s Interstellar Medium (ISM).

SUPER-THZ RECEIVER

The 4.7 THz receiver is based on a single pixel NbN hot electron bolometer (HEB) mixer [3] pumped by a 4.7 THz 3rd order distributed feedback quantum cascade laser (QCL) as local oscillator ([4]-[7]). The QCL is operated at 44 K using a commercial (Sunpower CT) Stirling cryocooler. The QCL, provided by MIT [8], emits ~ 150 µW at 4.7 THz and with tuning coefficients of 3 GHz/V and -160 MHz/K. The receiver has been characterized in the lab to determine sensitivity, IF bandwidth, stability, and beam pattern. We measure a double sideband receiver noise temperature of 815 K (~ 7 times quantum noise) with a noise temperature IF bandwidth of 3.5 GHz [2]. The output intensity of the QCL is stabilized using an auto gain control (AGC) loop [9] in which a voice coil shutter is driven to maintain the optimum bias conditions of the HEB, mitigating the effects of the 60 and 120 Hz modulation that are induced by the Stirling cooler free piston. The resulting increase in spectroscopic Allan variance time greatly improves the efficiency of on-the-fly mapping by increasing the period between calibration scans. In addition, the frequency of the QCL is stabilized using a superlattice harmonic mixer ([10], [11]) in which the IF output of the 24th harmonic of a 197.7 GHz source forms the input to a PID based frequency lock loop. These two control loops have been demonstrated to operate in parallel and independently. We describe the expected receiver performance in flight and outline the novel approaches to QCL amplitude and frequency stabilization.

MIXER PERFORMANCE

The HEB mixer used for the STO-2 4.7 THz receiver is a single pixel HEB in a quasi-optic configuration. The detector element is a 0.2 x 2 µm NbN superconducting bolometer (Tc = 9.1 K) coupled to a tight wound spiral antenna capable of operation from 0.6 to 6 THz. The HEB/antenna is coupled to a 10 mm diameter anti-reflection coated Si lens. Prior to integration into the instrument, the performance of the HEB mixer and QCL LO was characterized in the lab. For the HEB mixer, a standard hot/cold Y-factor technique was used. The experimental setup consists of a mixer mounted in a lHe cryostat with a 3 µm Mylar beamsplitter to combine the LO power with the vacuum hot and cold blackbody surfaces. For the LO source in these tests we used both a FIR gas laser at 4.3 and 5.3 THz and the flight QCL at 4.7446 THz. As indicated in Figure 1 below, we measure a DSB receiver noise temperature of 826 K at 4.7 THz.

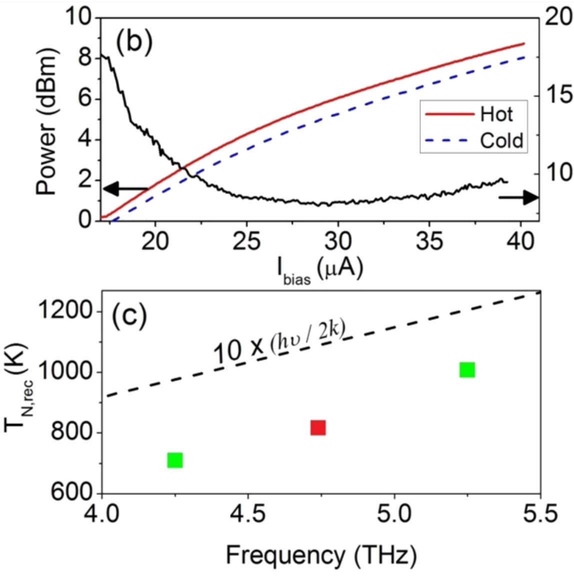

Fig. 1 (upper) DSB noise temperature of the STO-2 4.7 THz HEB as characterized in the lab using the flight QCL at optimum bias. (lower) Noise temperature versus frequency for the flight mixer at 4.3, 4.7 and 5.3 THz where green indicates the gas laser points and red indicated a QCL point.

LO PERFORMANCE

The 4.7 THz LO unit comprises a 120W Stirling cooler for 1 W heat lift from the QCL stage at 45 K. Special attention is given to the minimization of cooler vibration. This is achieved using an additional active balancer for the Sunpower CT cooler in which the vibration is sensed and actively compensated for by an additional inductive motor. This, coupled with frequency and amplitude stabilization schemes, results in an ultra-stable LO source. The thermal performance of the LO unit is as expected from the calculations reaching a base temperature of 44 K under a 0.7 W load from the QCL. Thermal stability is better than ± 0.1 K and cooling from room temperature to 44 K takes in the order of 45 minutes with payload coolant at 35 C. Radiation from the QCL is coupled to the HEB via a single parabolic metal mirror. The beam pattern plot in Fig. 2 shows the distribution of THz power at the equivalent position of the HEB Si lens, 750 mm away from the QCL. The majority the THz power falls within the diameter of the Si lens and is therefore easily possible to fully pump the mixer over a wide bias range of the QCL.

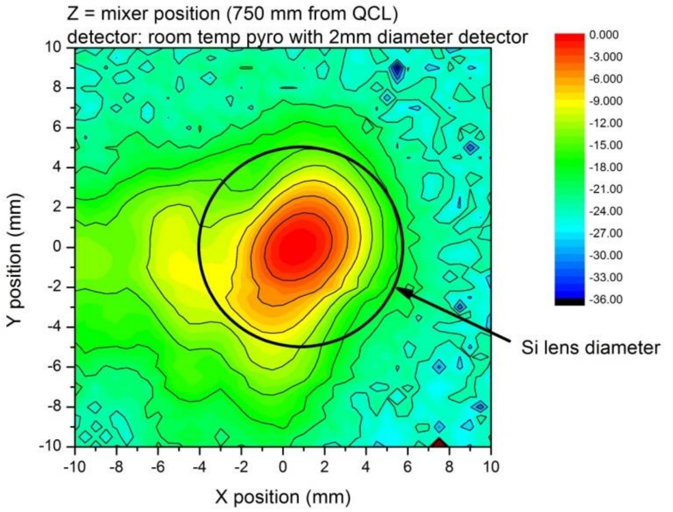

Fig. 2 Beam pattern measurement using a room temperature pyro-electric detector scanned in X and Y plane at the position of the HEB.(signal in dB)

RECEIVER PERFORMANCE

The performance of the complete 4.7 THz receiver was evaluated in-situ on the STO-2 payload. Fig. 3 shows an image of the installed LO hardware. The receiver noise temperature was measured at 1600 K @ 1.5 GHz IF and with a 12 µm Mylar beamsplitter. Initially, this thicker beamsplitter is used during alignment of the LO to the mixer so that pumping of the mixer may be more easily obtained. For flight, the beamsplitter will be replaced with a thinner membrane (6 µm) so that the system noise temperature will be reduced towards a predicted value of 1200 K. Receiver testing also demonstrated effective use of both the AGC and the superlattice frequency locking loops. In the latter, both the small residual 60/120 Hz modulation from the cooler and any slow drift in LO power could be reduced to a level that is no longer visible in the mixer IF. In addition, the effect of a small

(< 1 mm) movement in the alignment of the LO unit during elevation changes of the telescope from stow position (vertical) to horizontal was fully removed by the AGC loop.

The superlattice based frequency lock loop was also assessed whilst in-situ on the instrument. Frequency locking could be established using a 400 MHz IF tone produced by the 24th harmonic of a197.7 GHz AMC based LO. Free funning frequency stability was already shown to be excellent when running the QCL on the payload battery supply. With this favourable free running condition, the frequency locked line could be reliably established.

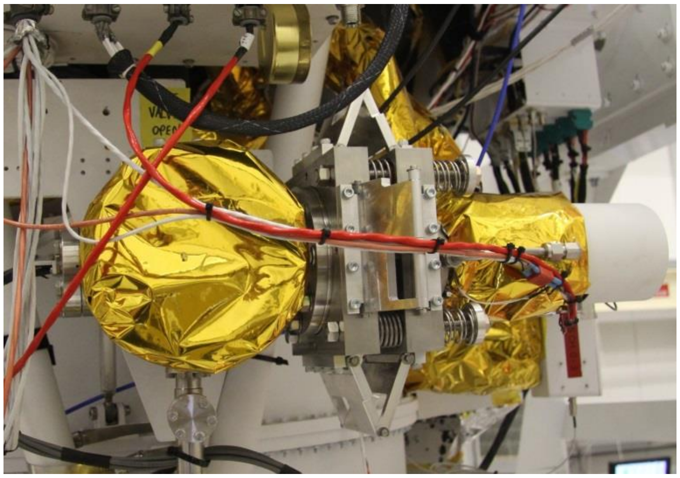

Fig. 2 The 4.7 THz QCL based LO as installed and ready for flight on the STO-2 payload

In addition to the FLL, the superlattice was also used to carefully characterize the frequency of the QCL versus bias voltage and QCL bath temperature. With this data, even in free running mode, the recorded values of bias and temperature could be used to determine the frequency of the QCL to within an estimated 10 MHz.

CONCLUSIONS

We demonstrate a QCL based 4.7 THz local oscillator and HEB mixer receiver for the STO-2 THz telescope. The receiver performs as predicted in terms of noise temperature, stability and optic coupling. The QCL based hardware is designed around a Sterling cooler to produce a turn-key LO system suitable for operation on a long duration stratospheric balloon. STO-2 is scheduled to fly in mid-December 2016.

REFERENCES

[1] Walker, C. K., et al. “The Stratospheric Terahertz Observatory (STO),” Proc. SPIE 7733, 77330N (2010).

[2] Kloosterman, J. L., et al.” Hot electron bolometer heterodyne receiver with a 4.7-THz quantum cascade laser as a local oscillator,” Appl. Phys. Lett. 102, 011123 (2013)

[3] Zhang, W., Khosropanah, P., Gao, J. R., Bansal, T., Klapwijk T. M., Miao, W., and Shi, S. C., “Noise temperature and beam pattern of an NbN hot electron bolometer mixer at 5.25 THz,” J. Appl. Phys. 108, 093102 (2010).

[4] Köhler, R., et al., “Terahertz semiconductor-heterostructure laser,” Nature, 417, 156-159 (2002)

[5] Williams, B. S., “Terahertz quantum-cascade lasers,” Nat. Photonics, 1, 517 (2007).

[6] Ren, Y., et al. “Terahertz heterodyne spectrometer using a quantum cascade laser” Appl. Phys. Lett. 97, 161105 (2010)

[7] Amanti, M. I, Scalari, G., Castellano, F., Beck, M., and Faist, “Low divergence Terahertz photonic-wire laser,” J. Opt. Express 18, 6390 (2010).

[8] Kao, T.-Y., Hu, Q., and Reno, J. L., “Perfectly phase-matched third-order distributed feedback terahertz quantum-cascade lasers,” Opt. Lett. 37, 2070 (2012).

[9] Hayton, D. J., Gao, J. R., Kooi, J. W., Ren, Y., Zhang, W., and de Lange, G., “Stabilized hot electron bolometer heterodyne receiver at 2.5 THz,” Appl. Phys. Lett. 100, 081102 (2012).

[10] D.G. Paveliev et al. “Experimental study of frequency multipliers based on a GaAs/AlAs semiconductor superlattices in the terahertz frequency range” Semiconductors 46, 125 (2012).

[11] D.J. Hayton, A. Khudchenko, D. G. Pavelyev, J. N. Hovenier, A. Baryshev, J. R. Gao, T. Y. Kao, Q. Hu, J. L. Reno, and V. Vaks, “Phase locking of a 3.4 THz third-order distributed feedback quantum cascade laser using a room-temperature superlattice harmonic mixer”, *Appl. Phys. Lett.*, vol. 103, 051115, (2013).