A 4.7 THz Heterodyne Receiver for a Balloon Borne Telescope

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ABSTRACT

We report on the performance of a high sensitivity 4.7 THz heterodyne receiver based on a NbN hot electron bolometer mixer and a quantum cascade laser (QCL) as local oscillator. The receiver is developed to observe the astronomically important neutral atomic oxygen [OI] line at 4.7448 THz on a balloon based telescope. The single-line frequency control and improved beam pattern of QCL have taken advantage of a third-order distributed feedback structure. We measured a double sideband receiver noise temperature ($T_{rec(DSB)}$) of 815 K, which is ~ 7 times the quantum noise limit ($h\nu/2k_B$). An Allan time of 15 s at an effective noise fluctuation bandwidth of 18 MHz is demonstrated. Heterodyne performance was further supported by a measured methanol line spectrum around 4.7 THz.

Keywords: Heterodyne, Terahertz, hot electron bolometer, quantum cascade laser, astronomy

1. INTRODUCTION

High resolution THz spectroscopy of astronomically important fine structure lines has the potential to provide detailed insight into the dynamics and the chemical processes within star forming regions. Historically, super-THz (>3 THz) heterodyne systems have not been widely available due to a lack of suitable local oscillator (LO) sources. The introduction of the THz quantum cascade laser (QCL) [1, 2] has had a significant role in opening the super-THz to heterodyne spectroscopy [3]. Heterodyne receivers are currently being developed to fly on the 2nd Stratospheric Terahertz Observatory (STO-2). Three high sensitivity cryogenic heterodyne receivers will be 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. The [OI] line at 4.745 THz has so far not been observed with high sensitivity due to technological constraints primarily associated with the availability of suitable local oscillator (LO) sources at this frequency. However, it is now possible for the first time to produce a compact, low power and highly sensitive heterodyne channel at 4.7 THz. The development of the 4.7 THz receiver for STO-2 is the main focus of this paper.

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STO-2 instrument description

Following on from STO [4], 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) [4].

The STO-2 platform is due to launch from McMurdo, Antarctica in late 2015. It consists of a balloon-borne observatory operating a 0.8 m diameter telescope giving a spatial resolution of 1 arcminute per pixel. The instrument gondola is carried by a NASA long-duration balloon (LDB) which gives the telescope a float altitude of ~ 36 km for 14 days or more.

The STO-2 instrument will utilize phonon cooled hot electron bolometer (HEB) mixers across 3 frequency channels centered at 1.4 THz (205 μm), 1.9 THz (158 μm) and 4.7 THz (63 μm), each with 1024 spectral channels and 1 MHz bandwidth. The 1.4 THz and 1.9 THz channels are similar to those flown on STO and each take the form of a 1 x 4 array of feedhorn coupled waveguide HEBs that are pumped by solid state amplifier multiplier chains (AMCs). Both the waveguide HEBs and the AMC LOs are developed by JPL. In parallel to the 1.4 and 1.9 THz channels there will be a single pixel 4.7 THz HEB/QCL receiver that is being developed by SRON, TUDelft and MIT[5].

2. 4.7 THZ RECEIVER

Local oscillator / QCL

The QCL has been key to extending heterodyne spectroscopy out to 4.7 THz. For the STO-2 4.7 THz receiver, a state-of-the-art distributed feedback (DFB) QCL is used [6,7]. This QCL, developed by MIT and fabricated using standard metal-metal waveguide techniques, employs a 3^{rd}-order DFB grating to provide significantly improved mode selectivity, far field beam and optical efficiency. The device demonstrated here has a width of 17 μm and 27 grating periods with an overall device length of ~ 0.76 mm. At 4.7 THz, this QCL offers the highest frequency so far reported using the 3rd-order DFB structure. Furthermore, by introducing an array of 21 DFB lasers [8] with a linear frequency coverage and a 7.5 GHz frequency spacing (approximately 1 per HEB bandwidth (DSB)), we can better target a specific LO frequency. These lasers benefit from relatively high efficiency requiring only 700 mW DC input power at 10-50 K for ~ 200 μW output power at 4.7 THz. The lasers have a bias tuning range of approximately 1.5 GHz with an electrical tuning coefficient of ~ 1 GHz/V and a thermal tuning coefficient of -150 MHz/K.

Operation of the QCL requires it to be cooled to below 50 K for optimum output power. To accommodate this in STO-2, a Stirling cooler will be used. The cooler selected is a Cryotel CT which is capable of up to 1 W cooling capacity at 40 K from 200 W DC input power. Operating the QCL at full cooling capacity results in a QCL base temperature of 36 K. The CT cooler offers an internal temperature control loop which can maintain a setpoint temperature to within ± 0.1 K. Vibration from the 60 Hz oscillating free-piston is controlled by either a passive or active damping mechanism. Figure 1 shows a beam pattern measured for the 4.7 THz QCL and cooled by the Stirling cooler. The QCL is directly mounted close to a UHMW-PE window and a pyroelectric detector is scanned in horizontal and vertical to measure the beam profile.

HEB mixer

The HEB is the preferred mixer for frequencies above 1.5 THz. For heterodyne mixing at 4.7 THz, we use a single pixel HEB in a quasi-optical configuration. The HEB is a 2 x 0.2 μm^2 superconducting NbN bridge coupled to a tight wound spiral antenna that is shown to give excellent response at super-THz frequencies up to at least 5.3 THz [9]. THz radiation is coupled into the HEB antenna using a 10 mm diameter Si elliptical lens, which is AR coated for ~ 25 % improved transmission.

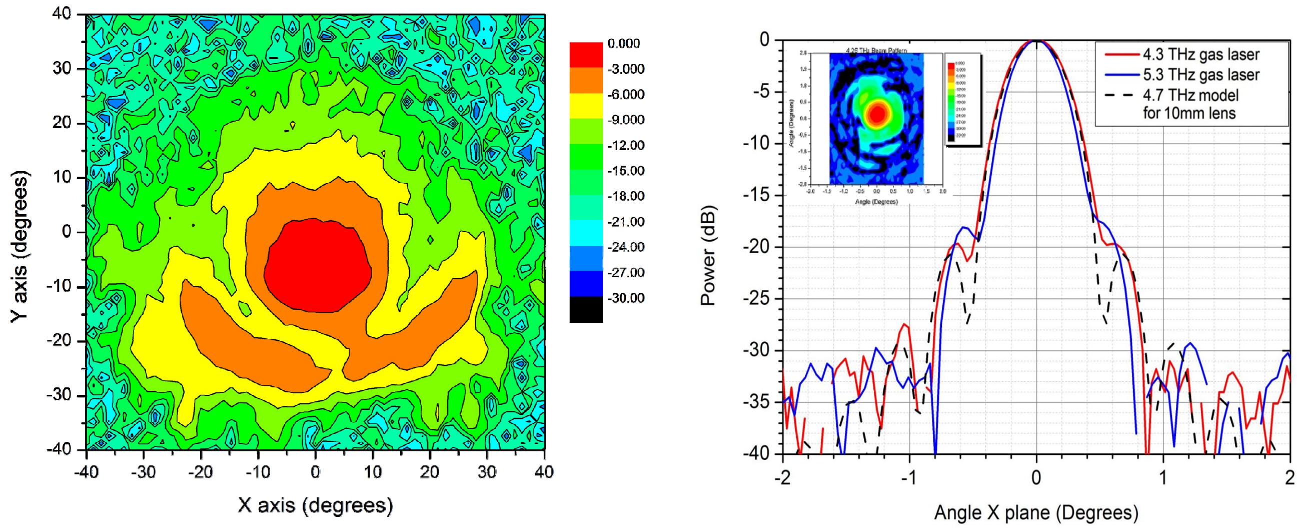

Figure 1. (left) The emission beam pattern of the 4.7 THz QCL (signal dB). The laser is mounted horizontally and inverted. (right-main) HEB beam patterns at 4.3 THz and 5.3 THz with a comparison to the PILRAP model. (right-inset) 2D beam pattern for 4.3 THz.

In order to confirm the expected coupling between the mixer and the telescope, beam pattern measurements have been taken using a FIR gas laser at 4.3 and 5.3 THz. These measurements were made by rotating and tilting the HEB mixer/Si lens around an axis located at the lens surface and measuring the signal detected by the HEB in direct detection mode. Fig. 1 shows the 2D beam pattern in the horizontal plane for 4.3 THz and 5.3 THz as well as for the model output from PILRAP. It shows the main beam to closely approximate that of the model. We also see side lobes that are at least 17 dB below the main beam. In the inset, we show a 2D beam map from 4.3 THz for a ± 20° x ± 20° area.

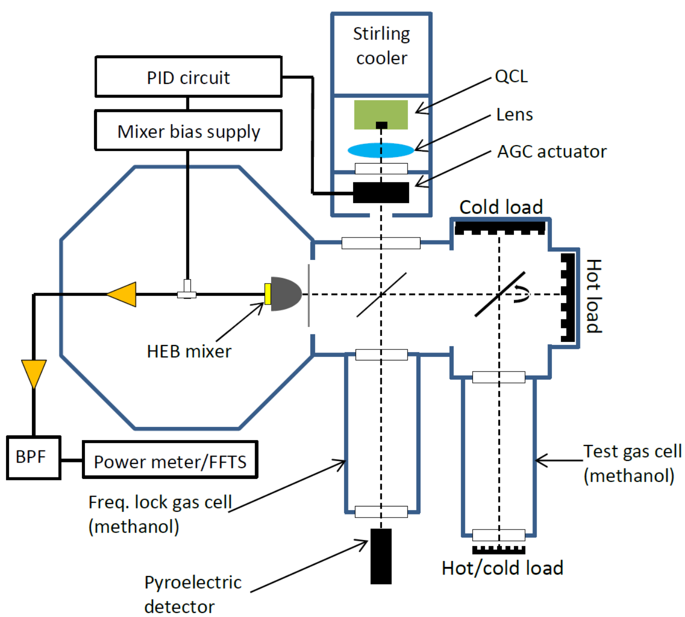

Figure 2. Schematic diagram of the 4.7 THz receiver setup for characterization in the lab.

QCL frequency locking

In its free running state the QCL is susceptible to frequency noise due to thermal and electrical fluctuations. As a result of this, the free running linewidth can be of the order of > 1 MHz which will clearly impose limitations on the achievable spectral resolution of a heterodyne receiver. The QCL therefore requires additional frequency or phase stabilization in order to realize the full resolution of the receiver. A reliable approach to this is to use a molecular transitional line as an absolute reference frequency [10, 11]. In this way a frequency discriminator can be produced using a simple gas cell containing any molecules that possess absorption lines in the spectral region of interest. For this receiver, methanol is chosen for its high density of lines in the vicinity of 4.7 THz.

The total power from the laser after passing through a 40 cm long cell containing methanol is detected using a room temperature pyroelectric detector. As the laser emission frequency sweeps through an absorption line, the detected power changes. By applying a small modulation to the laser frequency, and reading the detected ΔP using a PSD, the derivative of the absorption line is produced. It is then possible utilize the lock-in derivative signal in order to generate, via a PID circuit, a feedback signal to the QCL bias voltage in order to maintain a fixed frequency. Lab tests with a 3.5 THz QCL and more recently with a 4.7 THz QCL have demonstrated that the linewidth of the QCL can be reduced from ~ 1 MHz to ~ 50 kHz using the setup shown in Fig. 2.

Amplitude Stabilization

For instruments such as STO-2, mapping efficiency is greatly affected by receiver stability which determines the frequency of required off-source calibration scans. The Allan variance of a receiver provides a convenient method of determining the maximum useful integration time of a system. It is therefore desirable to maximize the Allan time of the receiver. HEB receivers have long suffered from stability issues due to the mixers susceptibility to changes in operating point caused by LO power fluctuations. Recent progress has been made in significantly increasing an HEB receiver Allan time by using the HEB direct detection response to actively control the LO power and therefore maintain a fixed HEB operating point [12]. By using this automatic gain control (AGC) technique, we are able to reduce noise contributions from both amplitude fluctuations in LO power, as well as mechanical misalignment which directly influence coupled LO power to the HEB. This is particularly important when operating the QCL with a Stirling cooler in which the residual 60 Hz mechanical vibration would otherwise hinder the mixer performance. This can be seen in Fig. 3 whereby a hot/cold load IF power time series is compared with and without the AGC running.

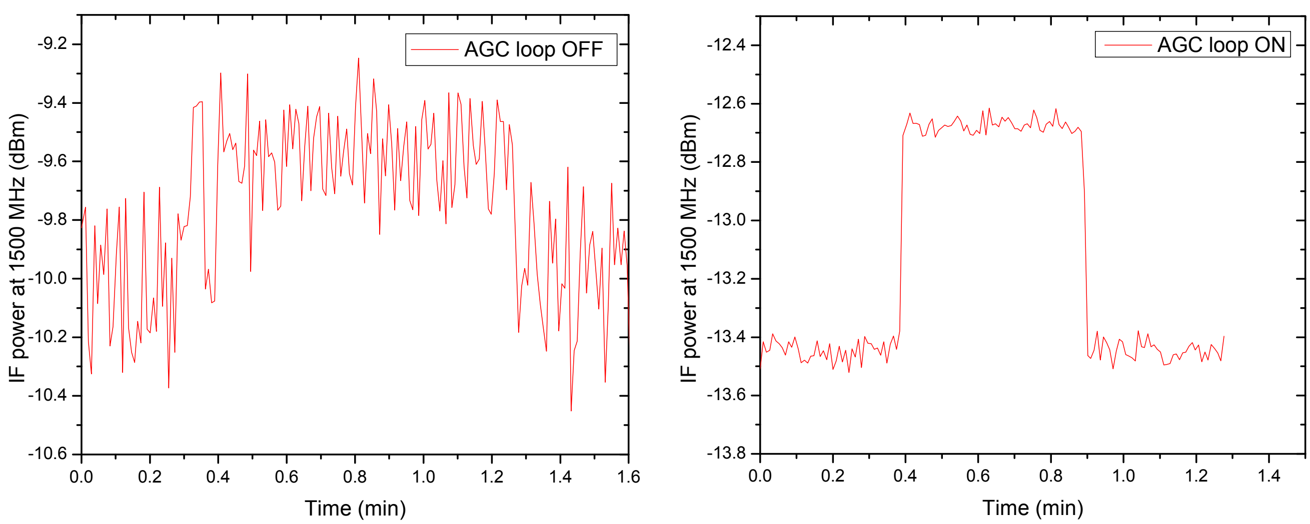

Figure 3. Comparison of 4.7 THz receiver IF power time series with the LO amplitude stabilization system (AGC loop) turned OFF (left) and ON (right). Traces are made at optimum HEB bias and at 1.5 GHz IF.

In this way, we have previously demonstrated a 4.7 THz receiver with a spectroscopic Allan time of 15 seconds and with an effective noise bandwidth of 18 MHz. Assuming that Allan variance is drift noise limited and by applying a standard correction to the 1 MHz channel bandwidth of the STO-2 spectrometer, we can estimate an instrument Allan time of approximately 1 minute during flight.

3. RESULTS

HEBs of the design that will be used for STO-2 have been extensively tested for performance in the lab. The devices are typically tested for noise temperature, IF bandwidth, beam pattern and spectral response.

An important measure of a heterodyne receivers performance is the IF noise bandwidth and gain bandwidth. Measuring the IF bandwidth using the AGC loop ensures that the HEB bias operating point remains constant for the duration of the measurement which can take several minutes using an RF spectrum analyzer. Without the AGC loop, there is always drift present in the LO power which leads inconsistency in the bandwidth measurements. The AGC loop therefore ensures that our noise bandwidth measurements are extremely reproducible even when comparing many different HEBs. It also allows for extended integration time during the measurement and so reducing the measurement noise as can be seen in Fig. 4.

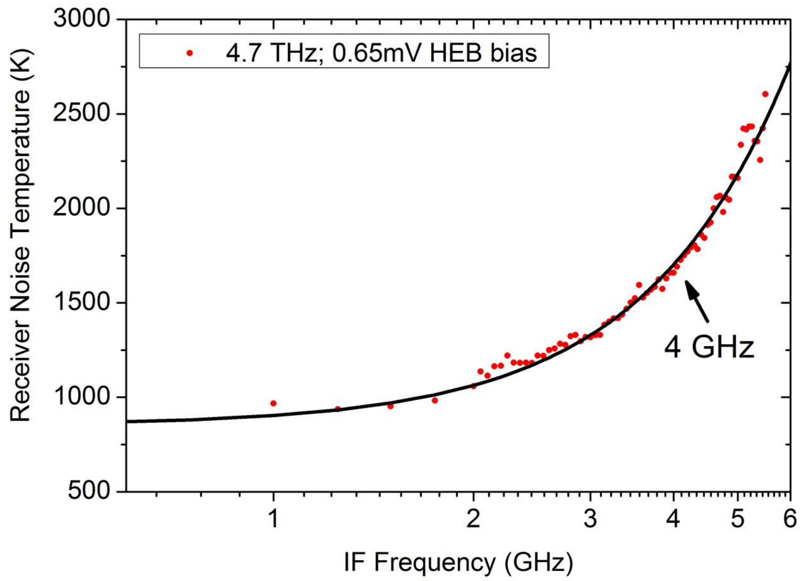

Figure 4. HEB IF noise bandwidth data measured at an optimal operating point.

To determine noise temperatures of the receiver, we use a standard hot/cold load Y-factor technique, which typically determines the device noise temperature over a range of bias points or LO power levels in order to find the optimum. Fig. 5 shows such a curve for a fixed bias voltage and swept LO power for a spiral antenna coupled HEB operating at a bias voltage of 0.7 mV with 4.7 THz LO and at 1.5 GHz IF. The LO power is swept by changing the setpoint of the AGC loop so that we may precisely step though a range of current points. We find the HEB optimum bias current of 29 μA which gives a receiver noise temperature (DSB) of 815 K for a required LO pump power of 220 nW and using a 3 μm Mylar (5%) beamsplitter. It should also be noted from this plot that the noise temperature is relatively insensitive to the operating current since between 25 μA and 35 μA, the noise temperature curve is relatively flat. This is considered to be an advantage when applying these mixers to an array with LO power variation between pixels.

To demonstrate that no additional noise is present due to use of a QCL as LO, we also measure the noise temperature of this HEB using FIR gas laser lines in the vicinity of 4.7 THz. Noise temperature is therefore measured at 4.25 THz and 5.25 THz as shown in Fig 5. We measure 750 K at 4.25 THz and 950 K at 5.25 THz with the same HEB receiver and see an approxiamtely linear relationship with frequency.

In order to demonstrate the functionality of the receiver for heterodyne spectroscopy, the receiver was used to measure a spectrum of methanol gas (CH_3OH). A methanol gas cell was attached to an external input port (Fig. 2) on the hot/cold vacuum setup so that there was no air in the signal path. In this case, the QCL was operated in a liquid He cryostat at a bias voltage of 11.8 V. The results, averaged over 18 s of integration time, are shown in Fig. 5 along with a simulation at 0.25 mbar that predicts line widths based on the frequencies and line strengths from the JPL spectral catalog [13, 14]. The lines from 1500 to 1700 MHz are attenuated because the FFTS upper band (1500–3000 MHz) high pass filter has a cutoff frequency of 1700 MHz. The best-fit frequency for the QCL is 4.740493 THz, which is close to the HEB bandwidth (~ 4 GHz) for the [OI] line. The verification of the JPL spectral catalog is also important for the frequency locking of the QCL.

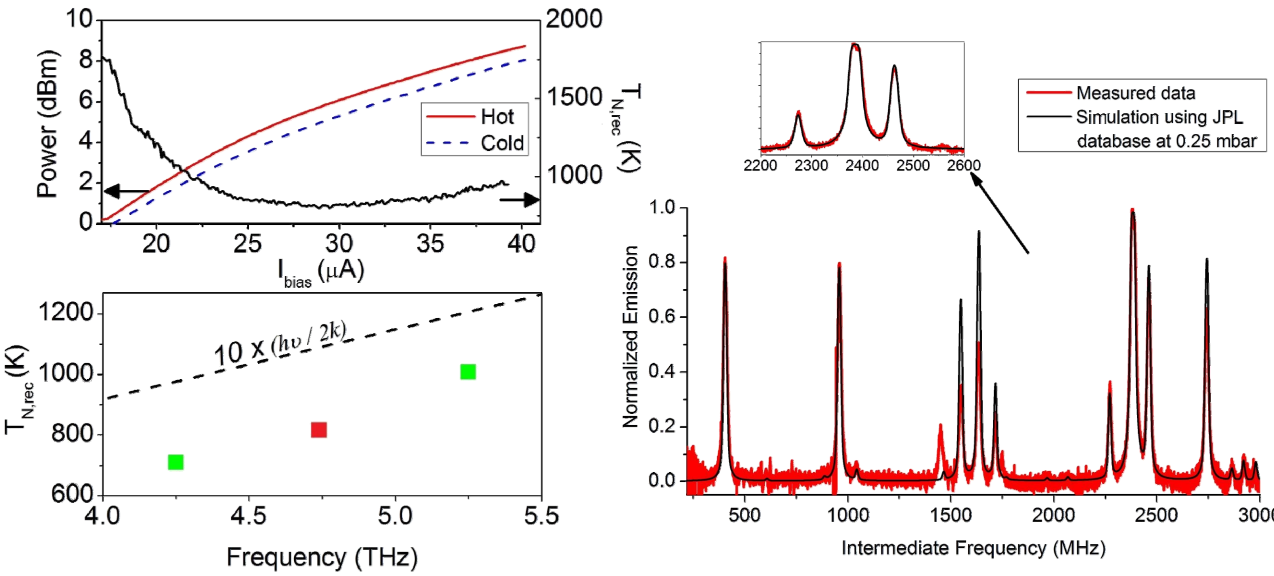

Figure 5. (left-upper) IF power measurements as a function of stabilized bias current with the calculated $T_{rec(DSB)}$ plotted on the right axis. (left-lower) $T_{rec(DSB)}$ for 4.3, 4.7 and 5.3 THz using a 3 μm beam splitter. A gas laser was used as a LO at 4.3 and 5.3 THz and a QCL was used as LO at 4.7 THz. For reference, 10 times quantum noise limit is also shown with the dashed line. (right) A DSB spectrum of methanol with a LO frequency of 4740.93 GHz compared with the predicted spectrum based on lines in the JPL catalog.

4. SUMMARY

We demonstrate a 4.7 THz HEB heterodyne receiver with DSB receiver noise temperature of 815 K that is being developed for the STO-2 instrument. We measure a receiver Allan time of 15 seconds with 18 MHz effective noise bandwidth and show an IF bandwidth of ~ 4 GHz. Heterodyne performance was verified by observing a methanol spectrum.

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