A novel terahertz heterodyne receiver based on a quantum cascade laser and a superconducting bolometer

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Abstract— **We report the first demonstration of an all solid-state heterodyne receiver that can be used for high-resolution spectroscopy above 2 THz suitable for space-based observatories. The receiver uses a NbN superconducting hot electron bolometer as mixer and a quantum cascade laser operating at 2.8 THz as local oscillator. We measure a double sideband receiver noise temperature of 1400 K at 2.8 THz and 4.2 K, uncorrected for losses in the optics, and find that the free-running QCL has sufficient power stability for a practical receiver, demonstrating an unprecedented combination of sensitivity and stability. The output power of the QCL is more than adequate for use with HEB's. The complete system provides a unique solution for high-resolution THz spectroscopy for astronomy as well as Earth science in space.**

Index Terms—**heterodyne receiver, mixer, superconducting hot electron bolometer mixer, quantum cascade laser, LO source, and terahertz.**

I. INTRODUCTION

Understanding of the complex astrophysics depends critically on the ability to perform high-resolution spectroscopy in the THz frequency region. There are about 4×10^4 individual spectral lines present in the interstellar medium (ISM), only a few thousand of which have been resolved and many of these have not been identified [1,2]. Detection of the emissions from the ISM is critical to the study of the cycle of gestation, birth, evolution, and death of stars and planets [3]. The THz region also covers all of the critical spectral emissions from the key molecules involved in atmospheric chemistry both on Earth and on the planets. Some of them have been identified as crucial to our understanding and monitoring of the global ozone depletion problem [4].

Heterodyne receivers are the only receivers that can offer very high spectral resolution ($\nu/\Delta\nu > 10^6$ where ν is the frequency) combined with quantum noise limited sensitivity [5]. A heterodyne receiver mixes an astronomical signal with a local-oscillator (LO) signal in a nonlinear element (mixer) to produce a signal at an intermediate frequency (IF), which is the difference between the LO frequency and astronomical signal frequency. The IF signal, normally at several GHz, is suitable for further amplification and spectral analysis. Present day heterodyne receivers use a combination of an electronically tunable solid state LO source [6], with either a superconductor-insulator-superconductor (SIS) [7] mixer or a hot electron bolometer (HEB) mixer [8,9]. The latter type of mixer is the detector of choice for frequencies above 1.5 THz. The Heterodyne Instrument for the Far Infrared (HIFI) on the Herschel Space Observatory[10], to be launched in 2007, is the first instrument to perform heterodyne spectroscopy using such receivers from 480 GHz to 1.9 THz in space.

Future space missions require improved angular resolution, improved sensitivity and, most importantly, an increase in frequency from 2 to 6 THz [2,11,12]. The development of new receivers operating at such high frequencies is limited by the availability of suitable LO sources. The existing solid state LO's are unlikely to generate sufficient output power at such high frequencies since the power falls off rapidly with increasing frequency due to reduced multiplication efficiency [6]. Optically pumped gas lasers can operate at higher frequencies but are in general massive, bulky, power-hungry, and not tunable. Such a gas laser is used in the Earth observing system microwave limb sounder (EOS-MLS)[13] launched by NASA in 2004 and is also planned for the 4.7 THz channel in the SOFIA airborne observatory [14]. The fact that these observatories are being built despite the obvious disadvantages of the gas lasers is a clear indication of the scientific driver to extend the frequency range of present day heterodyne receivers to higher frequencies, fed by the expected wealth of knowledge and new discoveries hidden in the THz range of the spectrum. Very recently, a new type of solid-state THz source was developed based on quantum cascade laser (QCL) structures [15]. This new source holds great promise for LO applications because of its compactness and high power efficiency. Here

Manuscript received May 2, 2005. The work in NL is supported by RadioNet and ESA. The work at MIT is supported by AFOSR, NASA and the NSF. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the US Dept. of Energy under Contract DE-AC04-94AL85000.

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we report the first demonstration of a fully operational heterodyne system at 2.8 THz based on such a THz QCL as LO source and a hot-electron bolometer as mixing element.

The concept of a QCL was first demonstrated in the mid-infrared ($\lambda \cong 4$ µm; 75 THz) by Faist *et al* [16]. Photons are created via electronic intersubband transitions in semiconductor heterostructures that take place entirely within the conduction band. Furthermore, in a QCL the heterostructure active region consists of a stack of repeated identical quantum well modules (typically 20-200), which enables a single electron to cascade down and emit a photon in each module. Due to this cascading effect, QCLs have large quantum efficiency and high output power. The QCL frequency range is determined by the energy spacing of the subbands, which is set by the design and growth of the quantum-well structure. The precise operating frequency is determined by the waveguide cavity of the laser. While the development of a THz QCL has proven to be more challenging than for mid-infrared QCLs because of the difficulty of achieving population inversion for small subband separations and of obtaining a low-loss cavity for long wavelengths, a first THz QCL was demonstrated at 4.4 THz by Köhler *et al* [15]. To be suitable as an LO, a QCL has to meet a number of essential requirements, such as single line lasing with a high spectral purity, continuous-wave (CW) operation, adequate output power, and good stability.

The work reported here uses a QCL-device described in Ref. 17, which is based on resonant phonon scattering to selectively depopulate the lower radiation level, while maintaining a long upper level lifetime. The active region contains 176 $GaAs/Al_{0.15}Ga_{0.85}As$ quantum-well modules grown by molecular beam epitaxy (MBE), with the total thickness of 10 µm. The cavity of the QCL is a double-sided metal-metal waveguide fabricated via Cu-Cu thermocompression wafer bonding, which provides low-loss mode confinement at THz frequencies. Similar QCLs have allowed lasing at lower frequencies down to 2.1 THz [18]. Although not taken advantage of in this work, these devices lase in CW mode up to 93 K [19]. The 25-µm-wide ridge waveguide was cleaved at both ends to form a 670-µm-long Fabry-Perot cavity (shown schematically in the inset of Fig. 1). The QCL is indium soldered to a copper mount and is attached to the cold plate of a Helium vacuum dewar. The main figure shows a typical spectrum of the QCL lasing at 2.814 THz (wavelength λ_0=106.6 µm), measured using a Fourier-transform spectrometer (FTS). It is biased with a DC current of 84 mA and dissipates a power of about 1 W. When operated in CW and free-running mode, a single lasing line is observed, with a linewidth of about 1 GHz, which is limited by the resolution of the FTS. The actual linewidth is likely to be much smaller, e.g. 30 kHz (measured in msec-time scale) [20] and 65 kHz (obtained over an arbitrarily long period of time using frequency/phase locking)[21]. The maximum output power is 1 mW, measured using a Winston cone in front of the QCL to collect all the radiated power. In a practical heterodyne experiment the available power will be limited by the divergence of the beam, the window size and the distance between the QCL and the first focusing element of the optics.

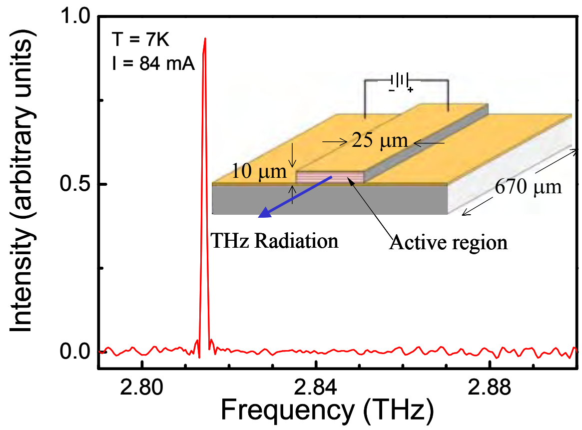

Fig. 1. Emission spectrum of the quantum cascade laser biased with a DC current I of 84 mA and operated at a temperature T around 7 K. The inset shows a schematic view of the QCL and the dimensions of the laser cavity.

In recent years phonon-cooled HEB mixers [22,23] have matured as the only sensitive mixer for the frequency range from 2 to 6 THz. It uses the response to radiation of the temperature-dependent resistance of a small NbN superconducting bridge [8]. The electrons (hot electrons) in the superconducting bridge are heated by the THz photons (predominantly by the LO signal) and the local electron temperature reaches the critical temperature of the superconductor. The mixing signal at IF is the result of the fact that the electron temperature can follow the beat-frequency of the LO signal and the signal to be detected. The sensitivity of receivers is characterized by their receiver noise temperature ($T_{N,\ rec}$) in Kelvin, which reflects the detection efficiency and the noise contributed by the mixer, and other factors such as the optics, the IF amplifier noise and the net transmission efficiency of the atmosphere. The HEB receivers have demonstrated superior sensitivity, e.g. a $T_{N,\ rec}$ of 950 K at 2.5 THz [23]. The principle of operation allows a wide frequency range, demonstrated up to 5.2 THz [22], and reaches an IF bandwidth of 6 GHz [23], reflecting the fast response of the electron temperature. Because of the small volume used, a HEB can operate with a very low LO power of 80 nW at the detector.

II. Measurement Setup

Figure 2 shows a schematic view of the experimental setup with the QCL and the HEB mounted in two separate dewars. A wideband spiral antenna coupled NbN HEB mixer is used with a superconducting bridge of 4 µm wide, 0.4 µm long, and about 4 nm thick. The normal state resistance R_N of the device, measured above the critical temperature of 9 K, is 65 Ω. Without radiation applied a critical current I_c of 320 µA is observed at 4.2 K. The radiation is coupled to the antenna using a standard quasi-optical technique: the Si chip with the

HEB is glued to the back of an elliptical, anti-reflection coated Si lens. The lens is placed in a metal mixer block, thermally anchored to the 4.2 K cold plate. When used with a gas laser at 2.5 THz a $T_{N,\,rec}$ is obtained of 1200 K [24] using identical optics and amplifiers as in the experiment with the QCL.

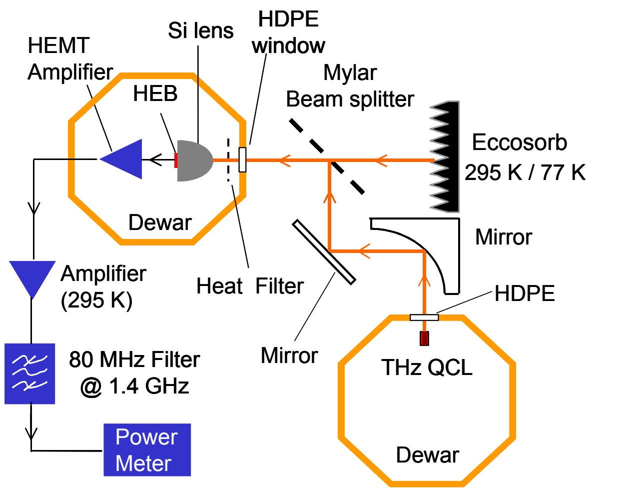

Fig. 2. Schematic view of the heterodyne measurement setup, where the mixer is a superconducting NbN hot electron bolometer (HEB) and the local oscillator is a quantum cascade laser. Both are operated in liquid-Helium vacuum dewars.

The divergent beam from the QCL passes through a high-density polyethylene (HDPE) dewar-window and is collimated with a parabolic mirror. The radiation is further guided to the HEB dewar through a flat mirror and a 6 µm thick Mylar beam splitter, which acts as a directional coupler. A blackbody source (of Eccosorb) is used as the signal, which defines a hot load at 295 K and a cold load at 77 K. The signal is combined with the QCL beam through the beam splitter. Both signals pass through the thin HDPE window and a metal mesh heat filter at 77 K of the HEB dewar. The total known loss is –16.2 dB for the QCL (to the HEB) optical path and –4.0 dB for the hot/cold load path. The IF signal, resulting from the mixing of the LO and the hot/cold load signal, is amplified using a low noise amplifier operated at 4.2 K, and is further fed to a room temperature amplifier and filtered at 1.4 GHz in a band of 80 MHz. The entire IF chain has a gain of 80 dB and a noise temperature of 4 K.

III. Results

A. Heterodyne sensitivity

The key result of this work is demonstrated in Figure 3. A set of current versus voltage (I-V) curves of the HEB is shown for various levels (270, 300, 330 nW) of the effective power of radiation absorbed at the HEB, together with the receiver noise temperature, $T_{N,\,rec}$, as a function of voltage. (The inset shows a top view of the HEB with its spiral antenna). The power level, which is estimated at the HEB by the isothermal technique [25], is varied by changing the DC bias current of the QCL. The noise temperature $T_{N,\,rec}$ is determined from the ratio of the IF output noise power for a hot and a cold load [24]. Each set of $T_{N,\,rec}$-V data shows a minimum region, indicating the optimum bias point. Best results are obtained for 300 nW LO power and 0.7 mV DC bias with $T_{N,\,rec}$ being as low as 1400 K, comparable to what was obtained with the gas laser at the lower frequency of 2.5 THz (with the same device and identical setup). The maximum power from the QCL coupled to the HEB, taking all losses into account, is estimated to be 14 µW. This is only about 1.4 % of the total output power available from the QCL, which is due to the poor optical coupling of the divergent beam. Besides, we also measured a small HEB (1 µm×0.15 µm×~4 nm) coupled with a twin slot antenna using the QCL as LO and obtained a $T_{N,\,rec}$ of 3200 K at 2.8 THz. It is interesting to note this device uses only 500 nW power at the QCL.

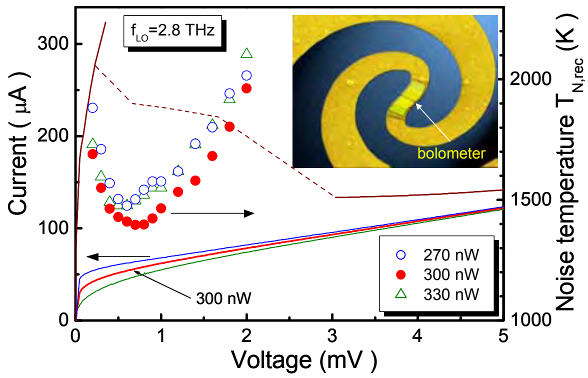

Fig. 3. Current-voltage characteristics (full lines, left axis) of a NbN hot electron bolometer (HEB) mixer without and with radiation from the QCL at 2.814 THz. The dashed line indicates an unstable bias region. The measured receiver noise temperature $T_{N,\,rec}$ (symbols, right axis) versus the bias voltage for different LO power levels at the HEB. The lowest value of $T_{N,\,rec}$ is 1400 K for 300 nW LO power and 0.7 mV DC bias. The bath temperature is 4.2 K. The inset shows a top view of the HEB with its spiral antenna.

B. The Allan Variance

We have performed two separate experiments to determine the stability of the HEB-QCL receiver, in which the HEB is operated at the point where it gives the lowest noise temperature. First, we measured the Allan Variance $\sigma^2_A(\tau)$ of the normalized IF output power, given [26] by $\sigma^2_A(\tau) \equiv ½\, \sigma(\tau)^2$, where σ^2 is the average squared standard deviation of each number from its mean and τ is the sampling period. The noise of any receiver is a combination of three terms: white (uncorrelated) noise, 1/f electronic noise, and low frequency drift. Since, to first order, only white noise can be integrated out, there is an optimum integration time, known as the “Allan” time T_A, beyond which the signal/noise ratio no longer improves [27]. A measurement of $\sigma^2_A(\tau)$ is a powerful tool to distinguish the various noise terms in a real receiver and to evaluate its optimal integration time. The measured $\sigma^2_A(\tau)$ for the HEB-QCL receiver is plotted as a function of the sampling period in Figure. 4. As a comparison we also plot $\sigma^2_A(\tau)$ obtained using a similar HEB mixer pumped by a phase-locked solid state LO at 1.5 THz [6]. Both measurements indicate an identical T_A of about 0.5 sec within the 80 MHz bandwidth of the IF chain. In the same figure we also include the measured $\sigma^2_A(\tau)$ when the HEB is biased at 10 mV, which shows the expected white noise behavior. This suggests that the observed "Allan" time is limited by the HEB mixer itself and not by any other sources, such as mixer bias, amplifier fluctuations etc. Secondly, we have measured the output power of the QCL as a function of time using the HEB as a direct detector. As shown in the inset of Figure 4, the averaged current of the HEB varies only 0.2 % in a period of 1000 seconds, indicating that the output power of a free-running QCL is sufficiently stable over a long time scale to maintain the HEB at its optimal operating point.

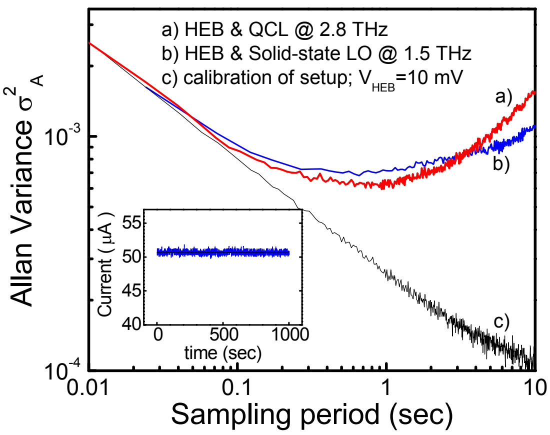

Fig. 4. Allan Variance σ^2_A of the normalized output power of the HEB as a function of the sampling period: a) for the HEB-QCL receiver at optimum operating point (red curve); b) for a similar HEB mixer at its optimum operating point using a phase-locked solid state LO operated at 1.52 THz (blue curve); c) for the receiver when the HEB is biased at 10 mV (black curve). The data is taken in a 80 MHz bandwidth around 1.4 GHz. The inset shows the current of the HEB at optimum operating point as a function of time. Its averaged value changes only 0.2 % in a period of 1000 seconds..

IV. CONCLUSIONS

In conclusion, we have demonstrated that a heterodyne receiver based on a QCL and an HEB can be operated with an excellent noise temperature of 1400 K at 2.8 THz. The free-running QCL has sufficient power stability for a practical receiver and the output power is more than adequate for use with HEB's. The key results described here have been accepted for publication [28].

The demonstrated QCL-HEB receiver can easily be extended to other frequencies in the range of 2-6 THz and with further optimization has the potential to reach (near) quantum noise limited sensitivity. It also offers the possibility of a multi-pixel array using one QCL as LO source, since the QCL output power is in principle sufficient for many HEB mixers. To achieve a wide frequency coverage and tunability one needs an array of QCL's, each with slightly different frequencies. We envision the QCL's, the HEB's and other components to be integrated together into a mechanical cryocooler at 4 K, leading to a compact, easy to use, rugged and space qualifiable all solid-state receiver system. Note that the beam pattern of a QCL was also studied [29] and a heterodyne measurement using a combination of a QCL and a HEB was also reported recently by other group [30].

ACKNOWLEDGMENT

We acknowledge J.W. Kooi for his advice on the Allan Variance measurement and G.N. Gol'tsman and B. Voronov for providing the NbN films. The work in NL is supported by RadioNet and ESA. The work at MIT is supported by AFOSR, NASA and the NSF. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the US Dept. of Energy under Contract DE-AC04-94AL85000.

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