2.5-THz heterodyne receiver with quantum cascade laser and hot electron bolometer mixer in a pulse tube cooler

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***Abstract*— A 2.5-THz heterodyne receiver has been realized in a pulse tube cooler. This liquid cryogen free system is based on a quantum cascade laser (QCL) acting as local oscillator and a hot electron bolometeric mixer. The double sideband noise temperature of the system is 2000 K and when corrected for optical losses in the signal path it is 800 K. A detailed study of the QCL beam quality yielded a beam propagation factor of 1.1-1.2.**

I. INTRODUCTION

The terahertz (THz) portion of the electromagnetic spectrum bears an amazing scientific potential in astronomy. High resolution spectroscopy in particular heterodyne spectroscopy of molecular rotational lines and fine structure lines of atoms or ions is a powerful tool, which allows obtaining valuable information about the observed object such as temperature and dynamical processes as well as density and distribution of particular species. Two examples are the HD rotational transition at 2.7 THz, and the OI fine structure line at 4.7 THz. These lines are main targets to be observed with GREAT, the German Receiver for Astronomy at Terahertz Frequencies, which will be operated on board of SOFIA [1]. Besides remote sensing, heterodyne detection has recently attracted significant interest for security applications, namely stand-off detection of hidden threats [2].

Hot electron bolometer mixer (HEB) have been recently pumped with QCL acting as LO [3][4]. As part of the receiver development for SOFIA we have developed a liquid cryogen-free heterodyne receiver for operation at about 2.5 THz. To build a compact THz-receiver, all front-end components which have to be cooled down for operation were integrated in a pulse tube cooler (PTC).

The performance of the QCL in terms of output power and beam profile as well as the double sideband noise temperature of the system is presented.

II. QUANTUM CASCADE LASER

A. Design

The 2.5 THz QCL used for this experiment is based on the so-called bound-to-continuum approach [5] with a rather uniformly chirped superlattice and no marked distinction between the injection and lasing regions [6]. The active medium is formed by 110 repeat units of the superlattice (total thickness 15 µm) covered on top by a Cr/Au layer. Between the <250 µm thick substrate and the active medium is a highly doped GaAs layer. This layer has two doping concentrations: $2.7\cdot10^{18}$ cm^{-3} in the 530 nm next to the superlattice and $2.6\cdot10^{17} cm^{-3}$ in the 500 nm close to the substrate. By these means the boundary conditions at the two sides of the buried doped layer can be controlled separately. This laser also has a Fabry-Pérot cavity that is 240 µm wide and 2.5 mm long. It has a maximum output power of 6 mW and operates up to 58 K in cw mode. More details such as light–current curves can be found in [6]. The laser was soldered to a copper bar, wire bonded, and mounted onto the first stage of the PTC. Without any heat load this stage has a minimum temperature of 31 K. During operation of the QCL this temperature rises to about 45 K.

B. Beam Profiles

To determine the quality of the laser beam it was focused with a TPX lens as shown in FIG. 1. The beam profiles were measured by scanning a Golay cell detector with a 0.4-mm diameter aperture in a plane orthogonal to the emission direction of the QCL at different positions in front and behind the position of the beam waist generated by the TPX lens.

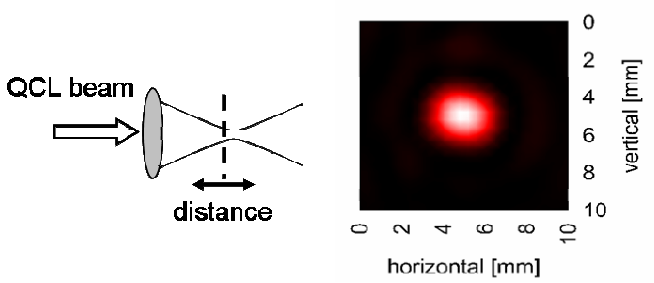

Fig. 1 Scheme for measuring the beam profile (left) and a typical beam profile at a position close to the beam waist (right).

The beam diameter at each position was determined according to the knife-edge method [7] and according to the second moment beam width method [8]. Both yielded the same results within the accuracy of the methods. The result for the knife edge method together with the calculated beam path is shown in FIG. 2. The beam waist is located ~63 cm from the QCL. At that position a second order polynominal fit (for a detailed description see [8]) yields a beam radius of 1.8±0.1 mm in direction vertical to the layers of the superlattice of the QCL and a M^2 of 1.1. In the orthogonal direction these values are slightly larger (2.0±0.1 and 1.2, respectively). Both results show that the beam propagation of the QCL can be sufficiently good described with Gaussian optics.

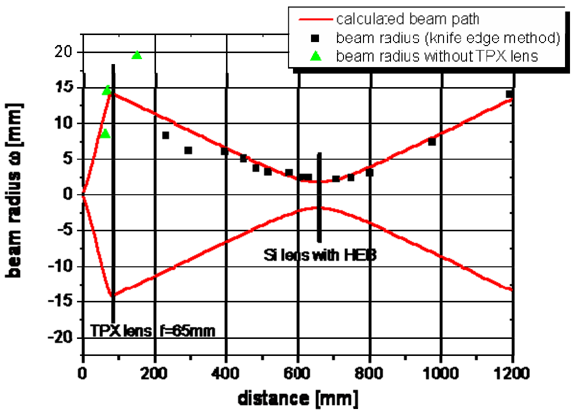

Fig. 2 Radius of the QCL beam (calculated with the knife edge method) without and when focused with a TPX lens. The QCL is located at the origin.

III. NOISE TEMPERATURE MEASUREMENT

A scheme of the measurement setup is shown in FIG. 3. All front-end components which have to be cooled for operation were integrated in a pulse tube cooler (PTC) which was a Gifford-McMahon type with two cold stages. Without any heat load the second stage has a minimum temperature of 2.3 K (31 K at the first stage) and rises to about 4.5 K (45 K at first stage). During operation the cooling power is 10 W and 0.8 W for the first and second stage, respectively.

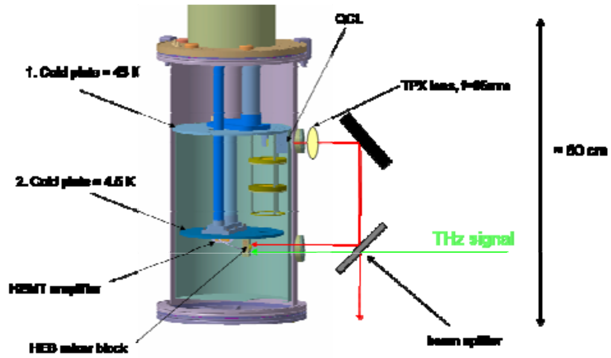

Fig. 3 Scheme of the heterodyne receiver in a pulse tube cooler. A radiation shield is mounted onto the first stage and is not shown here.

The previously described quantum cascade laser (QCL) is acting as local oscillator (LO) and mounted on the first stage of the PTC. A phonon-cooled NbN hot electron bolometer (HEB) is used as mixer. The HEB was a 2 µm wide, 0.2 µm long, and 5.5 nm thin NbN strip on a high resistivity (> 5 kΩ) silicon substrate located in the center of a planar logarithmic spiral antenna. It was glued onto the flat side of an extended hemispherical 12 mm diameter silicon lens. Together they were assembled in an aluminium holder which was mounted on the second cold stage of the PTC. The HEB mixer's IF port was connected to a bias-T which was used to feed the bias to the mixer and to transmit the IF signal to a low noise HEMT amplifier. This amplifier was also mounted onto the same stage of the PTC, but with some thermal insulation in order to provide an operation temperature of 10-15 K. The noise temperature of this amplifier is 5 K. A radiation shield with two windows was connected to the first stage of the PTC. A 1.1 mm thick z-cut quartz filter was mounted to the radiation shield in front of the HEB. Both vacuum windows (for the QCL radiation as well as for the input to the HEB) were made of 1-mm thick high density polyethylene (HDPE).

The output IF signal was filtered at 1.5 GHz with a bandwidth of 75 MHz, further amplified and rectified with a crystal detector.

The radiation from the QCL was guided by a plane mirror and a 6-µm thin Mylar beam splitter to the HEB. The TPX lens was positioned in order to provide a beam waist at the position of the HEB mixer.

The current-voltage (I-V) characteristics of the HEB at different values of LO power are shown in FIG. 4. The power from the QCL is sufficient to pump the HEB into the normal state (lowest I-V characteristic). The double sideband (DSB) receiver noise temperature was measured using the Y-factor technique, by presenting a room temperature blackbody and a blackbody cooled by liquid nitrogen to the input of the receiver. At a bias of 0.6 mV and 36 µA the lowest DSB receiver noise temperature of 2000 K was achieved.

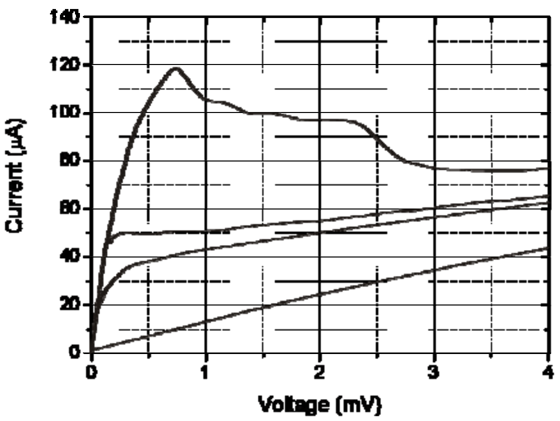

Fig. 4 I-V characteristics of a HEB mixer pumped with the QCL LO at 2.5 THz. The LO power is increasing from the uppermost curve (no LO power) to the lowest curve (HEB pumped into normal state).

FIG. 5 shows the output power of the QCL for different bias current and different temperatures of the first stage. The power is increasing with current and decreasing with temperature. For all temperatures it is possible to pump the HEB into the normal state.

The best noise temperature was achieved with ~45 µW QCL power in front of the cryostat window. Applying corrections for optical losses (antenna mismatch, absorption and reflection losses caused by the HDPE window and the quartz filter, reflection losses at lens surface without anti-reflection coating) to this power, this corresponds to an approximate power of 13 µW which is required to pump the HEB.

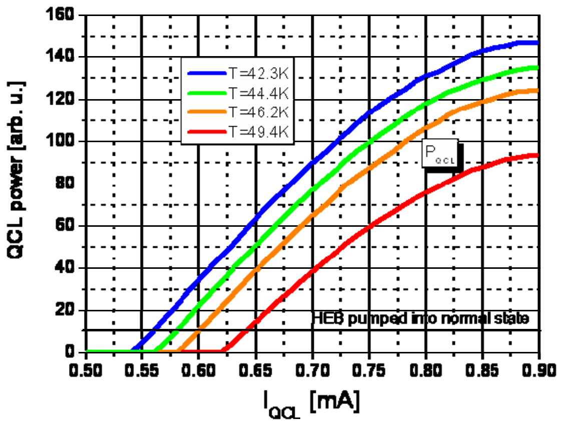

Fig. 5 Output power of the QCL for different bias and temperature.

The power absorbed inside the superconducting bridge as estimated by the isothermal method [9] is to be ~300 nW. The difference to the power needed to pump the HEB is probably attributed to a mismatch between the antenna pattern of the mixer and the beam profile of the QCL. Although the QCL beam has a close to Gaussian power distribution profile, it might be composed from a number of modes with different phase. Because the antenna of the HEB couples to only one mode out of these, there is a rather large difference between the power from the QCL and the power absorbed inside the HEB.

The IF output power demonstrated fluctuations with 1.2 Hz frequency, which corresponds to the piston movement of the PTC. This fluctuation has two origins: one is a small fluctuation of the QCL power and another one is a fluctuation of the bias point of the HEB. These effects added an uncertainty of ±200 K to the DSB noise temperature.

Taking into account the previously described losses the noise temperature of the receiver is ~800K which is comparable with other results [10][10].

CONCLUSIONS

We have successfully realized a liquid cryogen free THz heterodyne receiver front-end in a pulse tube cooler with QCL as LO and HEB as mixer. A detailed study of the QCL beam yielded a propagation factor of 1.1-1.2. The DSB noise temperature of the system is 2000 K and when corrected for optical losses in the signal path it is ~800K. This demonstrates, that a liquid cryogen free, turn-key heterodyne spectrometer for the frequency range from 2-6 THz is feasible.

ACKNOWLEDGMENT

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