Heterodyne receiver at 2.5 THz with quantum cascade laser and hot electron bolometric mixer

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ABSTRACT

Quantum cascade lasers (QCLs) operating at 2.5 THz has been used for gas phase spectroscopy and as local oscillator in a heterodyne receiver. One QCL has a Fabry-Perot resonator while the other has a distributed feedback structure. The linewidth and frequency tunability of the QCLs have been investigated by either mixing modes of the QCL or by mixing the emission from the QCL with the emission from a 2.5 THz gas laser. The frequency tunability as well as the linewidth are sufficient for Doppler limited spectroscopy of methanol gas. The QCLs have successfully been used as local oscillators in a heterodyne receiver. Noise temperature measurements with a hot electron bolometer and a QCL yielded the same result as with a gas laser as local oscillator.

Keywords: terahertz, heterodyne receiver, quantum cascade laser, local oscillator, hot electron bolometer

1. INTRODUCTION

The terahertz (THz) portion of the electromagnetic spectrum bears an amazing scientific potential in astronomy and atmospheric research. Many fundamental absorption and emission lines of astrophysical and atmospheric important molecules and atoms occur in this spectral region. Up to now more than one hundred molecules and atoms have been detected in space. There are fairly simple molecules such as CO but also molecules consisting of ten or more atoms have been identified. 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. Some examples are the CII fine structure line at 1.9 THz, the OH rotational transitions at 1.8 THz and 2.5 THz, and the OI fine structure line at 4.7 THz. Several upcoming missions are equipped with heterodyne receivers working above 1 THz. The heterodyne instrument for the far-infrared (HIFI) on the Herschel satellite will operate up to 1.9 THz [1]. SOFIA, the Stratospheric Observatory for Infrared Astronomy, will be equipped with two heterodyne receivers covering several frequency bands up to 4.7 THz [2-4], and TELIS, the THz and sub-mm limb sounder, has a frequency channel at 1.8 THz in order to measure OH in the atmosphere of Earth [5].

Typically, below ~2 THz multiplied microwave sources are used as local oscillator (LO). State of the art sources deliver as much as 20 µW power at 1.8 THz [6]. However, at higher frequencies, the output power is still too low. Above ~2 THz optically pumped gas lasers are used. They are relatively bulky and, more importantly, not tunable in frequency [4]. Recently developed THz quantum cascade lasers (QCL) are a promising alternative [7]. The lasing mechanism is based on intersubband transitions in the conduction band of heterostructures, most commonly made from GaAs/AlGaAs. Attractive features which have been demonstrated until now, are laser emission between 1.9 THz and 4.8 THz, operation temperatures up to ~160 K, high output power up to ~138 mW in continous-wave, single mode operation and narrow linewidth [8-13]. In this paper we will describe results regarding applications of a QCL as LO in a THz heterodyne receiver and in high resolution gas phase spectroscopy.

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2. QCL DESIGN AND PERFORMANCE

Two QCLs have been used for the experiments. Both are designed for an operation frequency at about 2.5 THz. One of the lasers has a Fabry-Perot resonator while the other laser is a distributed feedback (DFB) laser. The active medium of both laseres is based on a GaAs/AlGaAs superlattice and a plasmon-type waveguide. The design follows the so-called bound-to-continuum approach [14] with a rather uniformly chirped superlattice and no marked distinction between the injection and lasing regions. 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: 2.7×10^{18} cm^{-3} in the 530 nm next to the superlattice and $2.6\times10^{17} cm^{-3}$ 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. The resonator is a mesa-etched, 240 µm wide ridge with a length of 2.5 mm defined by cleaving. In contrast to the Fabry-Perot laser the top layer of the DFB laser is patterned into a series of narrow slits with half-wavelength period to create the DFB structure [15]. The lasers are soldered to a copper bar, wire bonded, and mounted on the cold finger of a mechanical cryo-cooler. In order to minimize vibrations it is mechanically isolated from the coldfinger by copper wires. The cooler has a heat extraction capacity of 1 W at 4 K. Since the input power of the laser is 5-10 W the smallest achievable temperature at the position of the QCL is ~20 K during laser operation. The laser threshold of both lasers is about 80 A/cm^2 at 20 K, the maximum output power is 6 mW, and the lasers work up to 58 K in continuous wave. Figs. 1 and 2 show the dependence between laser current, heat sink temperature and output power for the Fabry-Perot laser. It is important to note that due to the limited capacity of the cryo-cooler the operation temperature changes with current.

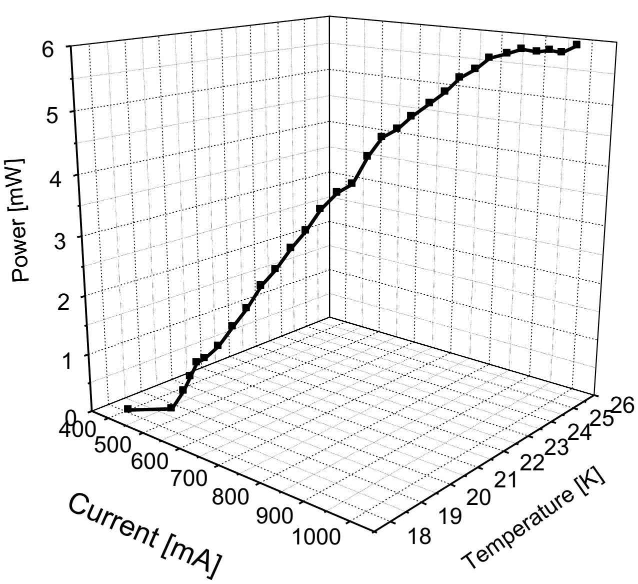

Fig. 1: Light-current-temperature curve of the Fabry-Perot QCL mounted in a mechanical cryo-cooler.

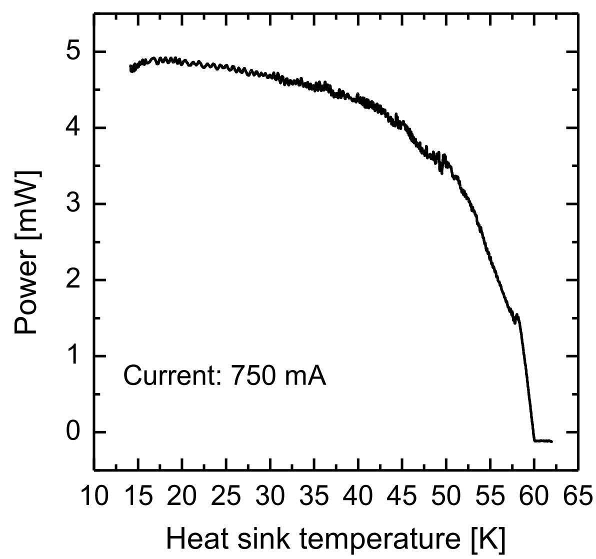

Fig. 2: Output power of the Fabry-Perot QCL as a function of heat sink temperature at a fixed current of 750 mA.

3. LINEWIDTH AND FREQUENCY TUNABILITY

In the case of the Fabry-Perot laser the linewidth was measured by mixing of its modes (homodyne mixing) as well as by mixing with the 2.5 THz line of an optically pumped gas laser (heterodyne mixing). For the DFB laser only heterodyne mixing is possible. In the homodyne experiments the laser modes were focused onto a GaAs Schottky diode with a quasi-optical 4λ corner cube antenna [16]. The signal at the difference frequency was amplified and analyzed with a spectrum analyzer (Fig. 3). In the heterodyne mixing experiment the radiation from the QCL was superimposed with the radiation from the gas laser operating on the methanol emission line at 2.5227816 THz (pump line of the CO_2 laser: 9P36 [17]) by a wire grid and focused onto the Schottky diode (Fig. 3). The difference signal was amplified and analyzed with a spectrum analyzer up to a maximum frequency of 18 GHz which was set by the available amplifiers. By this means the linewidth as well as the absolute frequency and the frequency tunability as a function of current and temperature were measured.

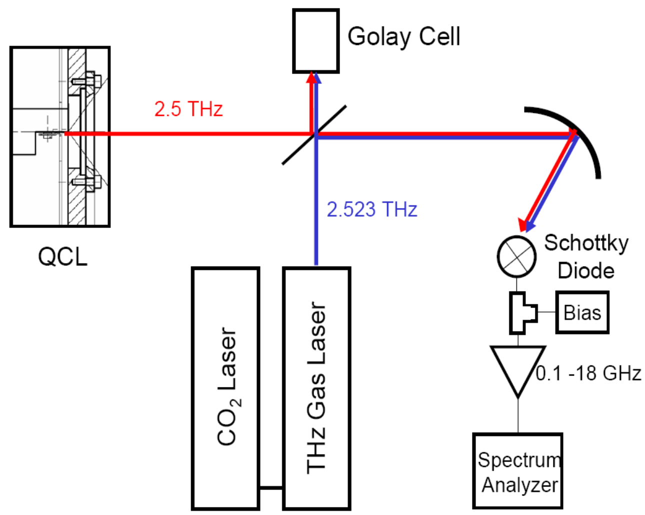

Fig. 3: Experimental set-up for homodyne and heterodyne mixing.

For homodyne mixing the Fabry-Perot QCL was driven with a current of 870 mA resulting in longitudinal modes with a separation of ~15 GHz. A Lorentzian fit to the profile of the mixing signal indicates a FWHM of ~30 kHz which is comparable with the resolution bandwidth of the spectrum analyzer (30 kHz) in a measurement time of 4 ms (Fig. 4). Assuming that both modes have the same width a single mode is less than ~20 kHz wide. The short term linewidth in the heterodyne mixing experiment was about the same as in the homodyne experiment. However, when averaging the difference signal for 60 s the width increased to 0.7 MHz (FWHM) and 2.4 MHz (at -10 dB) (Fig. 5). This widening is caused by temperature and current fluctuations in the QCL induced by the mechanical cooler.

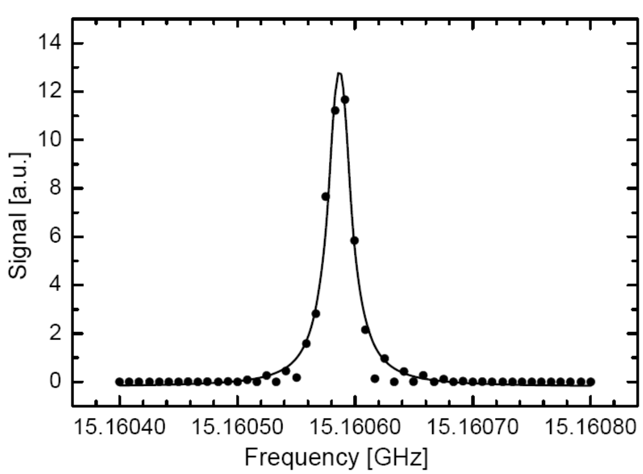

Fig. 4: Mixing signal of two longitudinal modes of the Fabry-Perot QCL.

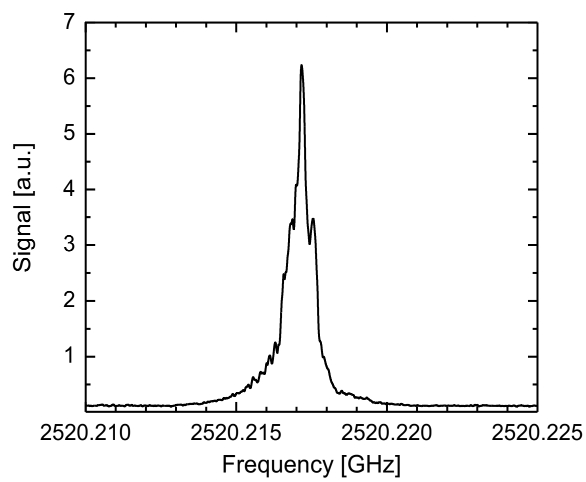

Fig. 5: Mixing signal of from the Fabry-Perot QCL and the 2.5 THz gas laser.

The frequency change of the laser emission as a function of current and temperature is displayed in Figs. 6 and 7. Three modes are in the band of the amplifier chain. The tuning rate for the three modes varies from +4.5 MHz/mA to +8.5 MHz/mA. Below about 530 mA only one mode exists. The frequency change with temperature depends on the mode and varies from -34 MHz/K to -44 MHz/K.

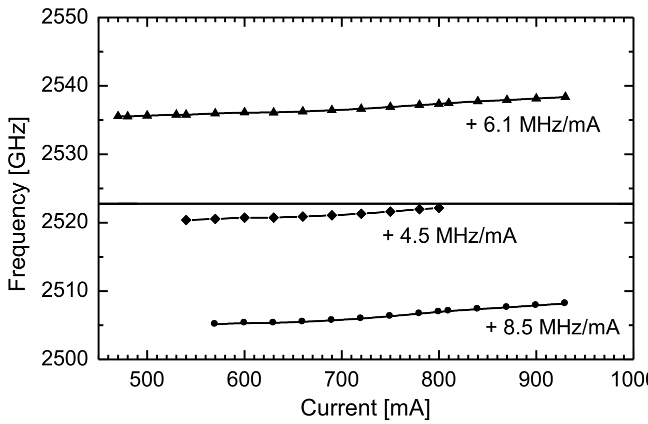

Fig. 6: Frequency of different modes of the Fabry-Perot QCL as a function of current (solid line: gas laser frequency).

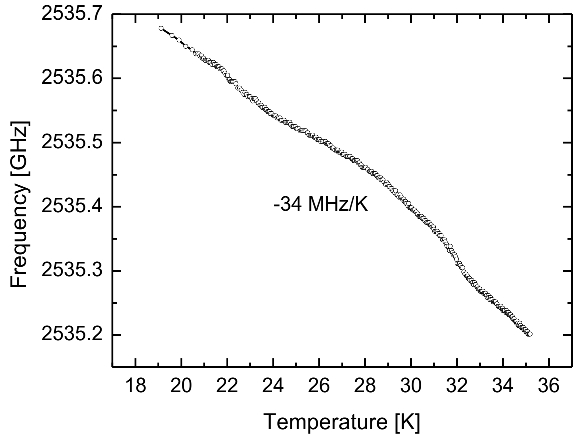

Fig. 7: Frequency of one mode of the Fabry-Perot QCL as a function of temperature.

For the DFB laser the tuning rate is +8.0 MHz/mA (Fig. 8). The temperature tuning varies between -20 MHz/K and -100 MHz/K depending on current and temperature (Fig. 9). For both lasers the tunability is mainly caused by changes of the refractive index with temperature and current.

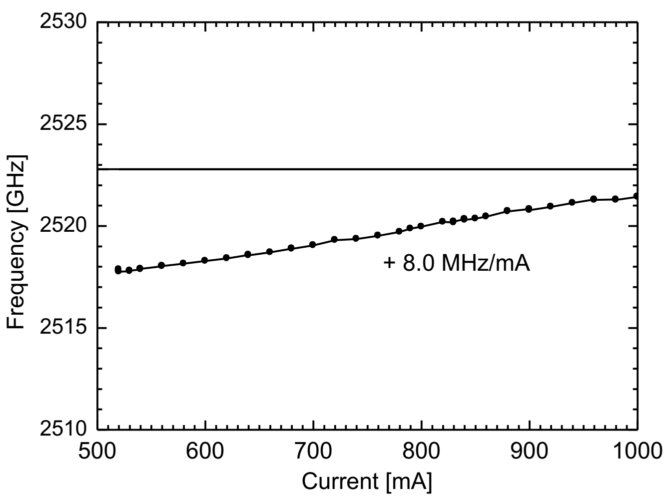

Fig. 8: Frequency of the DFB QCL as a function of current (solid line: gas laser frequency).

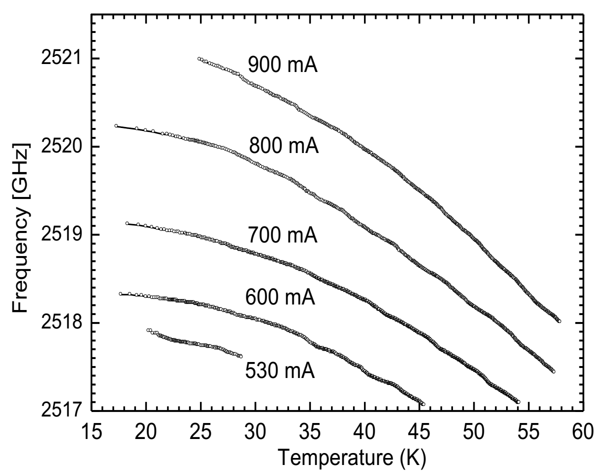

Fig. 9: Frequency of the DFB QCL as a function of temperature and current.

4. QCL AS LOCAL OSCILLATOR

The noise temperature of a phonon-cooled superconducting hot electron bolometer (HEB) was measured with the QCL acting as LO. For this measurement the Fabry-Perot QCL was operated just above threshold where it is still mono-mode. The HEB (for more details see [4, 18]) was a 2 µm wide, 0.2 µm long, and 3.5 nm thin NbN strip on a high resistivity (> 10 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 with a Parylene antireflection coating optimized for 2.5 THz [19]. Together they were mounted in a copper holder and put in a liquid helium cryostat equipped with a wedged TPX pressure window and a cold (77 K) quartz filter. The intermediate frequency (IF) signal was guided out of the mixer via the arms of the antenna and a 50 Ω coplanar line. A circulator was used to feed the bias to the mixer and to transmit the IF signal to a 4 K low noise HEMT amplifier. The output 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 focused by a TPX lens into the HEB and superimposed with the signal radiation by a 6 µm thick Mylar beamsplitter (Fig. 10). Since the dimensions of the outcoupling facet is in one direction much smaller than the operation wavelength and in the other one in the same order the beam profile of the laser is to a large extend determined by diffraction at the output facet (for a more detailed analysis see [20]). It consists of two parts: one originating from the active medium of the laser and another one from the substrate. However it is possible to transform the beam shape into close to Gaussian one by a single lens (Fig. 11). The DSB noise temperature was measured using the Y-factor technique in which a room temperature and a 77 K load were alternately placed in the signal path of the mixer (Fig. 10).

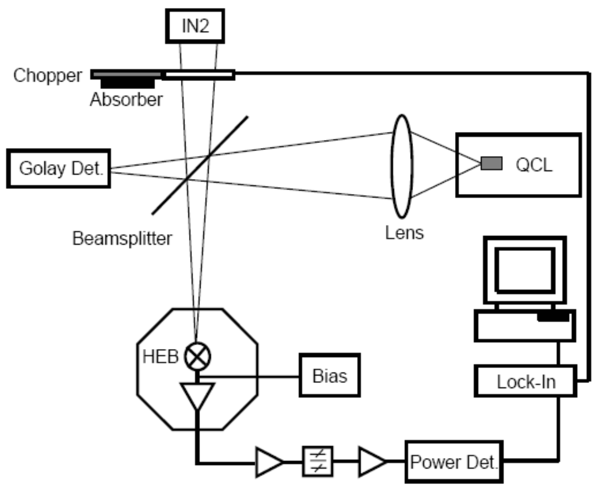

Fig. 10: Experimental set-up for noise temperature measurements with a QCL as LO and a super-conducting HEB mixer.

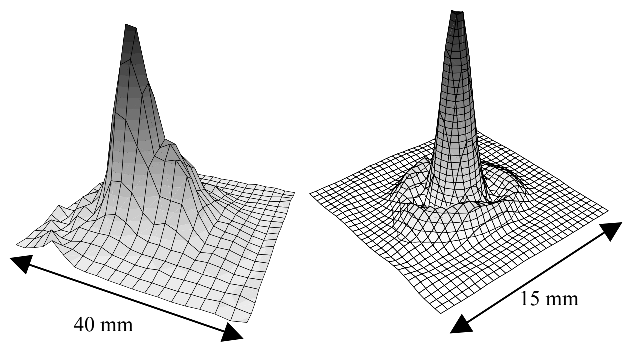

Fig. 11: Beam profiles of the Fabry-Perot QCL without lens (left) and with lens (right).

The current-voltage (IV) curves of the HEB as a function of LO power are shown in Fig. 10. The power from the QCL is sufficient to pump the HEB into the normal state (lowest IV curve). In order to achieve the lowest noise temperature the HEB was operated at 1.3 mV/38 µA (square in Fig. 12). This resulted in a double sideband (DSB) noise temperature of 2700 K. Even more important than the absolute value is the comparison with the noise temperature achieved with an optically pumped 2.5 THz methanol gas laser as LO. With this LO and the same experimental setup except for the TPX lens the same DSB noise temperature as with the QCL was measured. The optimal noise temperature was achieved for ~10 µW LO power in front of the cryostat window. With the gas laser LO ~7 µW were required which is somewhat less than with the QCL probably because of the better beam profile. The power inside the superconducting bridge as determined by the isothermal method [21] yields ~200 nW. The difference is due to losses in the optical elements and coupling losses between the beam pattern of the HEB antenna and the laser beam profile.

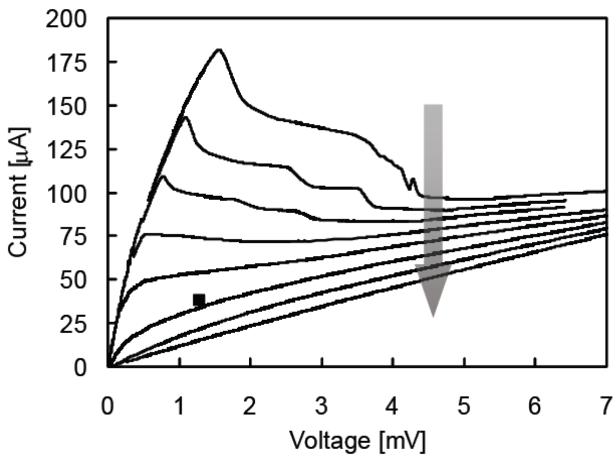

Fig. 12: IV curves of a HEB mixer pumped with a QCL at 2.5 THz. The arrow indicates increasing LO power. The square marks the position where the lowest noise temperature (2700 K DSB) has been obtained. It is worth noting that the same noise temperature has been achieved with a gas laser as LO.

5. GAS PHASE SPECTROSCOPY

The set-up of the spectrometer is sketched in Fig. 13. For frequency tuning the temperature of the QCL is set and the current is swept in steps corresponding to frequency steps of 0.5 MHz to 2 MHz. The set-up is similar to the heterodyne mixing set-up. The radiation from the QCL is reflected by a wire grid into a 0.5 m long absorption cell. The cell is equipped with two polyethylene windows and the pressure was measured with a capacitance manometer. For each measurement the cell was filled with methanol gas at a certain pressure and sealed off. The transmitted radiation is collimated by an off-axis parabolic mirror and detected with a Golay cell detector or a Ge:Ga photoconductive detector. The transmitted radiation was mechanically chopped in front of the detector and detected with a lock-in amplifier. A small part of the radiation from the QCL is transmitted through the wire grid. This is superimposed with the radiation from the gas laser operating on the 2.5 THz line. At the output of the gas laser a grid with wires oriented perpendicularly to the wires of the first grid was used to define the polarization in a way that it is reflected by the first grid. The radiation from both lasers is focused onto a GaAs Schottky diode [16]. The signal at the difference frequency is amplified and its frequency is measured with a spectrum analyzer. This is especially important because the frequency tuning of the QCL is not linear with current. The tuning range of the Fabry-Perot QCL is up to 3 GHz for each mode. From the DFB QCL a frequency range from 2.517 THz to 2.521 THz is available.

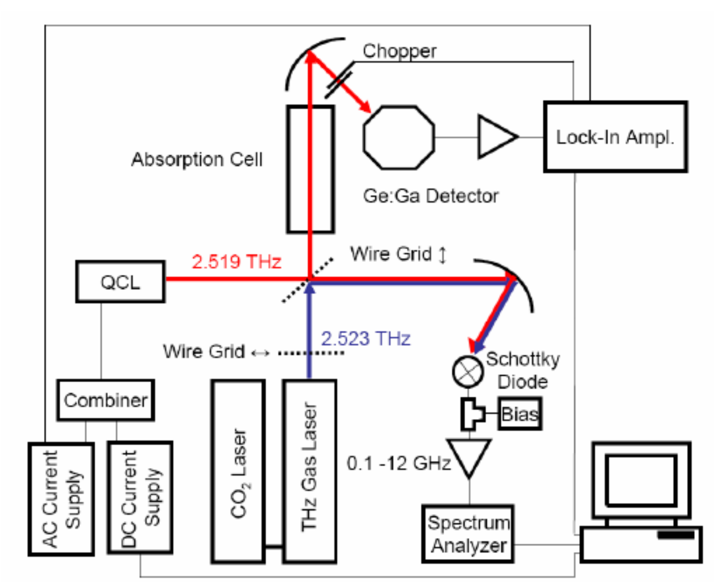

Fig. 11: THz spectrometer for high resolution gas phase spectroscopy.

As a demonstration we have performed absorption spectroscopy of several rotational lines of the methanol isotopomere $^{12}CH_3{}^{16}OH$. In Fig. 13 several spectra measured with the Fabry-Perot QCL at different pressures are shown. The pressure broadening is clearly visible.

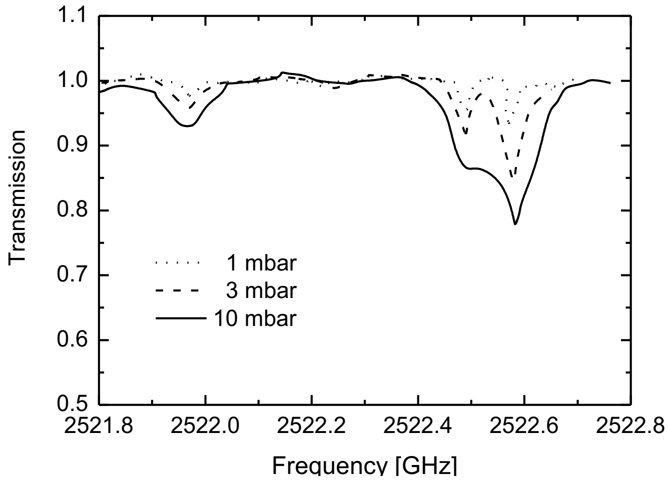

Fig. 13: Absorption spectra of $^{12}CH_3{}^{16}OH$ at different pressures measured with the Fabry-Perot QCL.

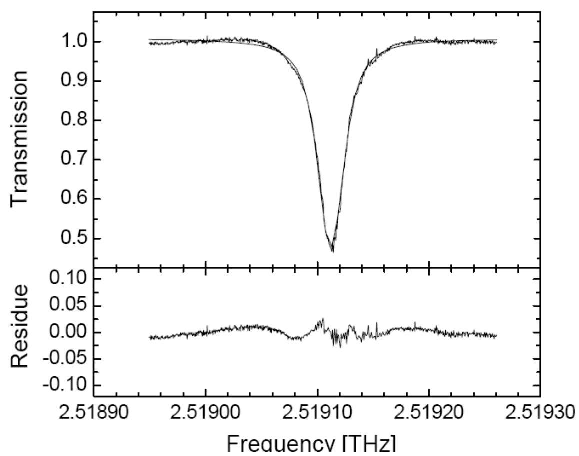

Fig. 14: $^{12}CH_3{}^{16}OH$ absorption spectrum measured at 100 Pa. The straight line is a fit of a Voigt profile to the absorption line. The lower panel shows the residue after subtraction of the fit from the measured data.

Fig. 14 shows the absorption line measured with the DFB QCL along with a Voigt profile fitted to the measured profile. As can be seen from the residue (measurement - fit) the agreement is very good. The center frequency of the absorption line is 2.519112(1) THz. This agrees well with published data measured with a Fourier transform spectrometer (2.519107(2) THz [22]). The self pressure broadening of the methanol line was determined by measuring its profile at different pressures up to 1000 Pa and determining the full width at half maximum (FWHM). A least squares fit to the FWHM data yields a pressure broadening coefficient of 229(2) kHz/Pa (Fig. 15). This is similar to pressure broadening coefficients of other methanol lines (265.6(2) kHz/Pa at 76 GHz [23] and 290 kHz/Pa at 2.524 THz [24]).

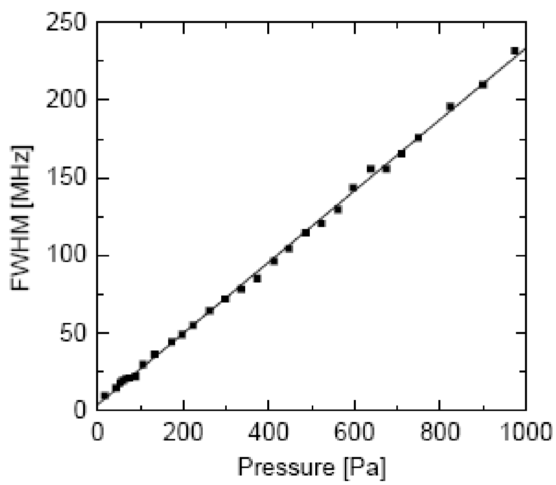

Fig. 15: FWHM of the CH_3OH transition as a function of pressure.

6. SUMMARY

In summary, the linewidth of two QCLs operating at 2.5 THz as well as their tuning rates as a function of current and temperature have been determined. One QCL has a Fabry-Perot type resonator while the other has a DFB structure. The QCLs were used as LO in a heterodyne receiver with a superconducting HEB mixer. The DSB noise temperature of the HEB mixer measured at 2.5 THz with a QCL was 2700 K. The same noise temperature was achieved when using a gas laser as LO. In addition a THz spectrometer for high-resolution gas phase spectroscopy based on a QCL as the radiation source has been realized. Frequency calibration of the spectra is achieved by instantaneously measuring the frequency difference between the QCL and a THz gas laser. We have measured the transition frequency and pressure broadening of a methanol line at 2.5 THz. The comparison of our data with other spectroscopic data shows good agreement. The results show that QCLs are very promising devices for high resolution spectroscopy and in particular as LO in an all solid state THz heterodyne receiver.

Acknowledgement

This work was supported in part by the Investitionsbank Berlin and the European Commission through the PASR project "TeraSec", the IP project "Teranova", and the Marie Curie RTN "Poise".

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