Experiences with Quantum Cascade Lasers as Local Oscillator

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Abstract— **This article describes the current status of THz quantum cascade lasers (QCLs)with respect to their use as local oscillator (LO). The main results regarding their beam pattern, emission linewidth, frequency tunability, and frequency/phase locking are summarized. Also noise temperature measurements with a QCL as LO and a superconducting NbN hot electron bolometric mixer are summarized.**

I. Introduction

Quantum cascade lasers (QCLs) are promising devices for use as local oscillator (LO) in a terahertz (THz) heterodyne receiver. They are unipolar lasers based on intersubband transitions in the conduction band of heterostructures, made from GaAs/AlGaAs [1, 2]. Since the first demonstration of the laser effect at THz frequencies [3] different concepts for the active medium as well as for the waveguide have been realized [2]. The active medium might be roughly divided into three groups: chirped superlattice, bound-to-continuum, and resonant-phonon design. The chirped superlattice provides two relatively broad minibands: one for the upper laser state and one for the lower laser state [3]. The bound-to-continuum design is based on a chirped superlattice but the upper laser level consists of a single (bound) state [4]. The resonant-phonon active medium makes use of the LO phonon in GaAs, which couples the lower laser state resonantly with the upper laser state of the adjacent quantum well [5]. Essentially two types of waveguides are in use: the surface-plasmon waveguide and the metal-metal waveguide. The surface-plasmon waveguide consists of a thin, highly doped layer between the active medium and the substrate and a metal layer on top of the laser ridge. It has relatively low loss but suffers from an incomplete overlap of the laser mode with the active medium, because the laser mode extends significantly into the substrate. The confinement factor (a measure for the fraction of the laser mode which is confined in the active medium) for this type of waveguide is around 0.5. The metal-metal waveguide has a metal layer instead of the doped layer between the active medium and the substrate. Therefore it has a confinement factor of 1 but higher loss than a laser with the same active medium but a surface-plasmon waveguide.

Relevant features which have been demonstrated and which are especially important if a QCL is going to be used as LO are [3]: emission between 1.2 THz and 4.9 THz, a maximum operation temperature of 130 K, and an output power of up to ~138 mW. It is important that all values have been obtained in continuous wave mode (in pulsed operation these values are somewhat higher) and without applying a magnetic field, which can be used to lower the emission frequency, but is not very practical for a LO. In the following sections the status of the development of QCL-based THz LOs will be reviewed. It is not intended to describe every experimental detail. Instead emphasis is put on pointing out the key features obtained by different groups. For details the reader is referred to the original publications.

II. Beam Pattern

Although QCLs have large output power compared to multiplied microwave sources, pumping of a mixer such as a hot electron bolometer (HEB) might not be a straightforward task since the beam of the QCL has to be matched to the beam pattern of the mixer antenna. While for single pixel receivers the coupling efficiency between QCL and mixer does not need to be very high, an array receiver will require a very well shaped LO beam, normally a Gaussian beam profile or in other words a beam propagation factor M^2 close to one. M^2 is the ratio of the angle of divergence of a laser beam to that of an ideal Gaussian beam with the same diameter at the position of the beam waist.

A. QCL with Surface-Plasmon Waveguide

The beam profile of such a laser consists of two lobes. One is emitted from the laser ridge and another one from the substrate (Fig. 1) [6, 7]. In addition a fringe pattern appears around the lobes. This structure is more pronounced for lasers with short wavelength while at wavelengths above about 100 µm the lobes start to merge due to diffraction effects. By integrating the signals of the two lobes and the fringe pattern separately the confinement factor for a 4.3 THz laser was determined to be 0.49 which is in good agreement with the computed value of 0.47 [6]. In the direction vertical to the layers of the superlattice the width of beam pattern (ridge lobe as well as substrate lobe) is determined by a single aperture. The fringe pattern corresponds to a diffracting aperture which has about the size of the substrate and ridge (assuming plane wave illumination and a refractive index n = 3.7). In direction orthogonal to this the full width at half maximum (FWHM) is a determined by λ/w with λ the emission wavelength and w the width of the ridge.

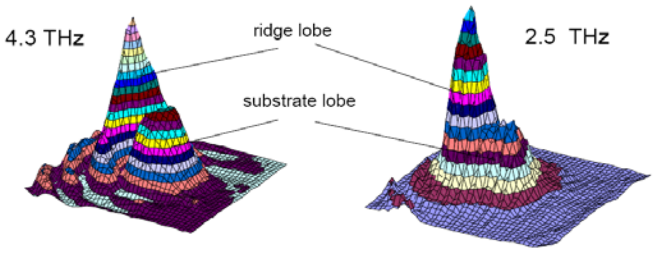

Fig. 1: Beam patterns from two QCLs with surface-plasmon waveguides operating at 4.3 THz and at 2.5 THz.

In order to determine M^2 for a 2.5 THz QCL the beam profile was in a plane orthogonal to the emission direction of the QCL at different positions in front and behind the position of the beam waist created by a TPX lens [8]. The beam diameters were determined according to the so called knife-edge method In Fig. 2 the beam radii of two orthogonal cuts through the beam profile are plotted as a function of distance from the QCL. The beam radius at the position of the waist is 1.8±0.1 mm and the M^2 is 1.1 in direction vertical to the layers of the superlattice. Parallel to the layers the beam radius and M^2 are slightly larger (2.0 ±0.1 mm and 1.2, respectively).

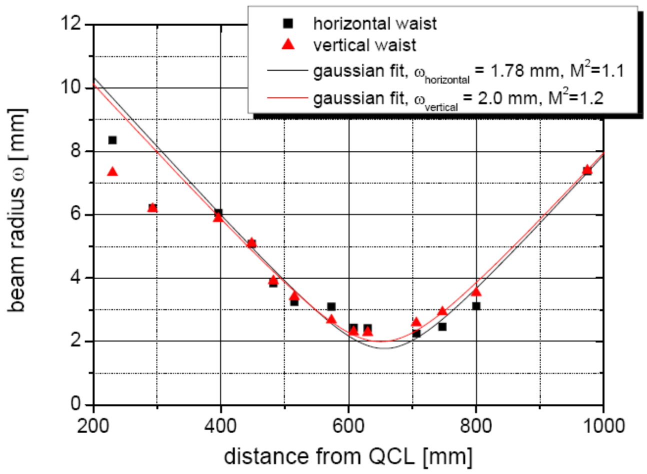

Fig. 2: Beam propagation of a QCL with surface-plasmon waveguide (vertical: in direction parallel to the superlattice layers, horizontal: in direction orthogonal to the superlattice layers).

For use as a LO the beam of the QCL was transformed with a single TPX lens in order to match the beam pattern of the QCL with the HEB antenna. The overlap integral between the main lobe of the QCL profile and a Gaussian beam yields a coupling efficiency of ~70% [6]. Taking into account the non-Gaussian beam profile of the QCL this can be considered as an excellent value.

B. *QCL with Metal-Metal Waveguide*

The beam pattern of a QCL with metal-metal waveguide is much more divergent than that of a surface-plasmon QCL. The lobe structure is not observable. Instead a pronounced ringlike pattern exists [9]. This results from the far field interference of the coherent radiation emitted by all facets of the laser ridge [10]. Despite the bad beam pattern it has been shown that such as laser can be used as LO. Although coupling of LO radiation to the mixer is very inefficient.

Therefore, several methods have been developed in order to improve the beam pattern of a QCL with metal-metal waveguide. These are a silicon lens at the output facet [11], a horn antenna at the output facet of the ridge [12], or a wide area surface emitting structure [13]. However, none of these approaches has resulted in an improved beam profile when compared to the surface-plasmon waveguide QCL.

EMISSION LINE WIDTH AND FREQUNCY/PHASE LOCKING

Initially, the linewidth of the QCL emission was measured by beating of two laser modes of a free running QCL with a multi-mode Fabry-Perot resonator. An upper limit of about 20 KHz (FWHM) could be established by this method [6, 14]. Phase locking of two longitudinal modes of a 2.7 THz QCL has been demonstrated. The beat linewidth was less than 10 Hz. Under frequency stabilization line profile was found to be Lorentzian with a minimum linewidth of ~6.3 kHz [15].

The frequency of a 3 THz QCL has been locked to that of a THz gas laser with a tunable microwave offset frequency [16]. The locked QCL linewidth was 65 kHz (FWHM). The lock condition could be maintained indefinitely. No temperature or bias current regulation of the QCL other than that provided by the lock error signal was required. The result demonstrates that a THz QCL can be frequency controlled as needed when used as LO. Instead of a gas laser which is not a very practical source for providing the reference frequency a solid state multiplier source can be used. The result of such a locking scheme is shown in Fig. 3. The frequency of the QCL is locked against the signal generated from a microwave source by a superlattice multiplier [17].

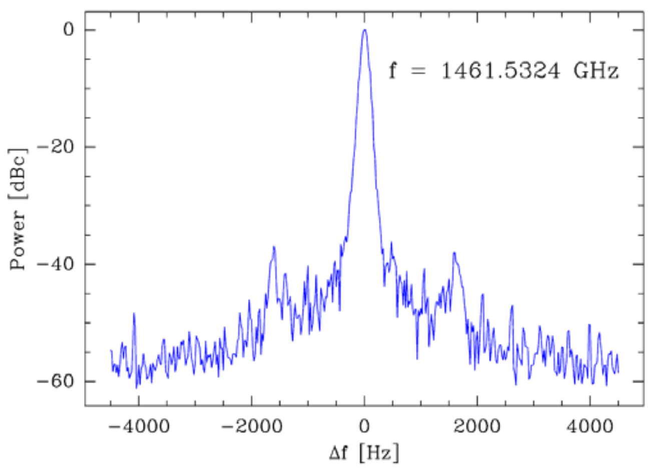

Fig. 3: Frequency locking of the emission of a 1.46 THz QCL against the signal generated by a superlattice multiplier (courtesy: U.U. Graf, D. Rabanus, Universität zu Köln).

III. FREQUENCY TUNEABILITY

The frequency of a QCL can be tuned by either applying a sweep current, by changing its temperature, or by an external resonator. A linear change of the laser emission frequency with current has been found from emission spectra recorded by a Fourier transform spectrometer (FTS) ($1/f\ \Delta f/\Delta I \approx -5.5\times10^{-2}\ A^{-1}$) [18] and by mixing of the QCL radiation with that from a THz gas laser ($1/f\ \Delta f/\Delta I \approx -1.0\times10^{-3}\ A^{-1}$) [14]. Temperature-related shifts of the frequency have been reported ranging from $1/f\ \Delta f/\Delta T = -1.9\times10^{-5}\ K^{-1}$ to $-5.1\times10^{-5}\ K^{-1}$ [18, 19] over a temperature range from 20 to 35 K and 15 to 47 K, respectively. Significantly larger current-related and temperature-related tuning parameters have been observed for resonant-phonon QCLs ($-1.5\times10^{-2}\ A^{-1}$, $-6.61\times10^{-5}\ K^{-1}$ [16]). Excluding mode hopping [18], the QCL laser frequency was reported to be linearly tunable by the current as well as the laser temperature. The changes in the emission frequency were attributed entirely to temperature changes of the refractive index of the active medium independently whether they originate from variation of the current or from variation of the temperature [14]. The tuning rate of a bound-to-continuum laser with surface plasmon waveguide was found to be in the order of $1/f\ \Delta f/\Delta I \approx +3.0\times10^{-3}\ A^{-1}$ (Fig. 4) [20].

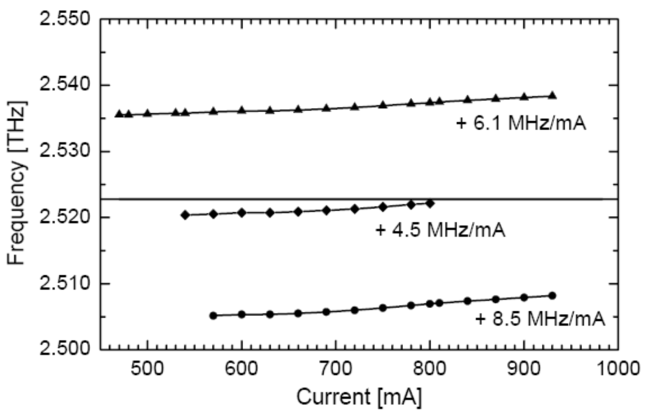

Fig. 4: Frequency tunability of a multi-mode QCL with Fabry-Perot resonator. The straight line is the frequency of the gas laser against which the QCL frequency was measured.

Recently it was reported that the emission frequency of a resonant-phonon QCL with sub-wavelength microdisc resonator changed the sign of the tuning rate from a negative ($-0.57\ A^{-1}$) to positive ($+0.14\ A^{-1}$) value with increasing applied electric field. This was attributed to a shift of the maximum of the gain curve by the quantum confined Stark effect [21]. In general resonant-phonon QCLs seems to have a larger tunability with current than lasers with bound-to-continuum or chirped superlattice design of the active medium.

However, none of the tuning rates is sufficient for an LO. Integration of the QCL into an external cavity has been shown to be a possible solution for extension of the frequency tuning range [22]. In this experiment the external cavity was realized by one facet of the QCL and the reflection from a movable mirror. The other facet was coated with SiO_2 which served as antireflection coating. Broad and fine tuning of the frequency were achieved by varying the cavity length. Coarse tuning up to ~90 GHz was obtained near the center frequency of 4.8 THz, and continuous mode-hop-free tuning was observed over ~10 GHz.

IV. MOLECULAR SPECTROSCOPY

High resolution molecular spectroscopy is an important test in order to demonstrate the performance of a heterodyne spectrometer. Spectroscopy with a heterodyne spectrometer with a QCL-based LO has not yet been performed. However, as a first step in this direction high resolution absorption spectroscopy with a QCL has been done [23]. The spectrometer is sketched in Fig. 5. For frequency tuning the temperature of the QCL is set and the current is swept. By this means the frequency range from 2.517 THz to 2.521 THz is available. The radiation from the QCL is reflected by a wire grid into an absorption cell. The transmitted radiation is either mechanically or electrically chopped and detected with a Ge:Ga detector. A small part of the radiation from the QCL is transmitted through the wire grid, superimposed with the radiation from a 2.5 THz gas laser and focused onto a GaAs Schottky diode. The difference frequency is measured for each data point. This is important because the frequency tuning is not linear with current and there was not frequency locking to a reference source.

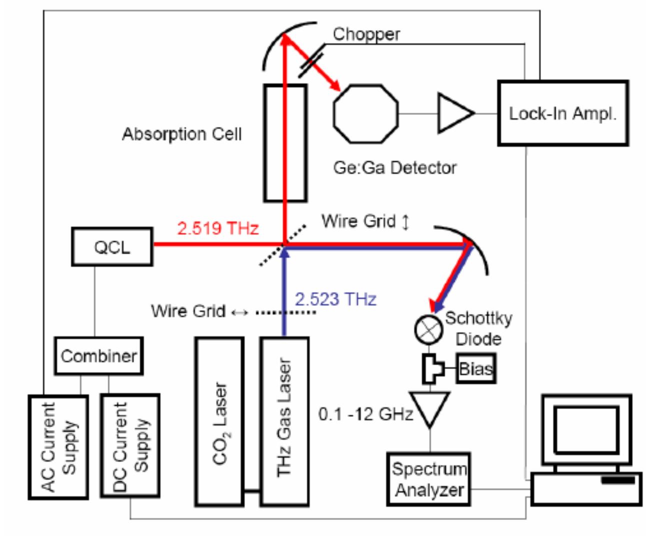

Fig. 5: Set-up of a THz absorption spectrometer with QCL.

In Fig. 6 a typical absorption spectrum of a rotational transition of $^{12}CH_3{}^{16}OH$ is shown along with a fit of a Voigt profile. The agreement is very good. By measuring the profile at different pressures the pressure broadening as well as the pressure shift were determined. Both agree well with published data. Since the measured molecular linewidth is not limited by the linewidth of the QCL it can be concluded that the QCL performs well for high resolution spectroscopy.

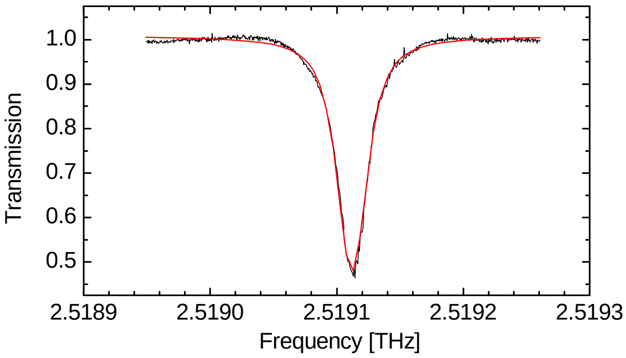

Fig. 6: Absorption line of $^{12}CH_3{}^{16}OH$ measured with the THz spectrometer (black line) and fit of a Voigt profile (red line).

V. NOISE TEMPERATURE MEASUREMENTS

The measurement of the noise temperature of an HEB mixer was among the first experiments on the way towards a QCL based LO [6, 24]. Gao et al. [24] measured a double sideband (DSB) noise temperature of 1400 K at 2.8 THz. The receiver had a NbN hot electron bolometric mixer and a resonant-phonon LO with metal-metal waveguide. Only 1.4% of the power from the QCL was coupled into the HEB, due to the poor optical coupling of the divergent QCL beam to the mixer. The Allan stability time of the QCL/HEB receiver was found to be the same as the one measured for an HEB mixer pumped by a multiplier LO. With a surface-plasmon QCL a noise temperature of 1150 K was obtained [25]. The improved was attributed to an improved mixer and an optical setup with lower loss. It is worth noting, that the gain bandwidth of a HEB mixer gas been measured for the first time above the superconducting gap of NbN by mixing the radiation from a THz gas laser with that from a frequency tunable QCL [26].

In another experiment [6] with a QCL with surface-plasmon waveguide the optimal noise temperature was achieved for ~10 µW LO power in front of the cryostat with the HEB mixer. With a gas laser LO ~7 µW were required for the same mixer, which is somewhat less than with the QCL, probably because of the better beam profile of the gas laser.

Recently, a liquid cryogen free THz heterodyne receiver with a QCL and an HEB mixer was demonstrated [8]. The front-end of the receiver is integrated in a pulse tube cooler (PTC). The QCL is mounted on the first stage of the PTC and operates at a temperature of about 45 K while the HEB is mounted on the second stage of the PTC (~4.5 K). At the position of the HEB the beam profile is close to Gaussian (inset in Fig. 7) allowing for an efficient coupling of the LO radiation into the mixer. With this setup the HEB mixer was pumped into the normal state (Fig. 2). The double sideband noise temperature measured with this set-up was 2000 K and when corrected for optical losses in the signal path it was ~800 K. This experiment demonstrates that a solid state THz heterodyne receiver in a PTC is feasible.

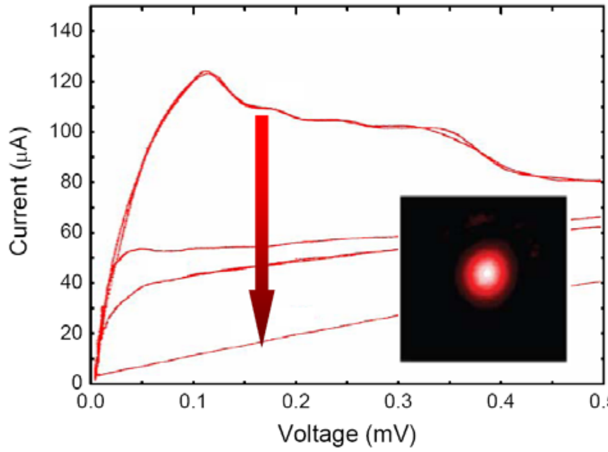

Fig. 7: Pumped IV-curves of an HEB mixer. The arrow indicates increasing pump power. The inset shows the beamprofile measured at the position of the HEB mixer. The area shown is 10x10mm^2.

OUTLOOK

Since the first demonstration of a THz QCL in 2002 significant progress has been made towards a QCL as LO for a THz heterodyne receiver. It has been shown that the fundamental requirements for this application can be met. However a practical LO is still missing. A major challenge remains to realize all required specifications in a single device. Also, the input power or alternatively the laser threshold has to be lowered so that the laser can be operated at liquid nitrogen temperature or in a small Stirling cooler. Once these issues are solved THz QCLs will be a valuable LO in heterodyne receivers especially at frequencies above 2 THz.

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