Beam Pattern Measurements on Quantum Cascade Lasers Operating at 2.8 THz

Aurèle J.L. Adam, J. Niels Hovenier, Irmantas Kasalynas, Tjeerd O. Klaassen, Jian-Rong Gao, Benjamin S. Williams, Sushil Kumar, Qing Hu, Ekaterina E. Orlova and John L. Reno

***Abstract*—Quantum cascade lasers operating in the THz region are of great potential interest as local oscillators for THz heterodyne detection. To assess the applicability of this new source as LO, a study of the properties of the emitted radiation, like beam shape and optical phase front, is very important. In this paper we will present results of the beam profile of 'metal-metal' cavity QCL's using the conical section method, designed for spherical antenna pattern measurements. It appears that, contrary to earlier waveguide based simulations, the beam patterns show strong angular intensity oscillations.**

***Index Terms*—Beam profile, Local oscillator, Quantum cascade laser, THz radiation**

I. Introduction

The development of TeraHertz technology has been severely hindered by the lack of versatile sources. For long, one had to rely on bulky optically pumped far-infrared lasers or on complicated systems based on either frequency *multiplication* of high frequency microwave radiation (typically 80–100GHz) or on generation of radiation at the frequency *difference* of two (VIS/NIR) diode lasers. The quest for new sources has resulted recently in the development of the Quantum Cascade Laser (QCL) [1]. After the first demonstration of emission in the mid-infrared range ($\lambda \approx 4$ μm; 75 THz)[2], now Quantum Cascade Lasers (QCL) are operating CW in the THz range, down to 2.1 THz ($\lambda \approx 143$ μm)[3]. These sources are very promising as local oscillators for heterodyne detection, especially for frequencies above 2 THz where the usual frequency multiplier systems do not provide enough output power. In order to use the QCL for that purpose, apart from the frequency and power stability, one also needs to investigate the pattern of the emission beam. This latter issue is very important because, in order to keep the electrical dissipation of these cryogenic devices low, the dimensions of the active region should be reduced as much as possible. As a result, the dimensions of the waveguide cavity may turn out to be of the order of, or even smaller than, the emission wavelength. We will report for instance on the beam pattern of a QCL, emitting at λ = 107 μm, with a 650 x 25 x 10 μm^3 metal-metal cavity. A set-up has been build to measure the beam pattern of QCL's in the near- and far field region. It consists of a Helium flow cryostat with optical windows, offering a wide angle of view (up to 120º full cone angle). The THz intensity is measured using a pyroelectric detector, mounted on a two-axis rotation system. We will report on beam patterns of QCL bars with a metal-metal cavity of various dimensions, emitting at 2.8 THz.

A.J.L. Adam, J.N. Hovenier, I. Kasalynas, T.O. Klaassen and J.R. Gao are with the Kavli Institute of NanoScience, Faculty of Applied Sciences, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands. (phone:+31.15.2786136 ; fax:+31.15.2783251;e-mail: t.o.klaassen@tnw.tudelft.nl)

B.S. Williams, S. Kumar and Q. Hu are with the Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge MA 02139, U.S.A.

E.E. Orlova is with the Institute for Physics of Microstrucutres, Russian Academy of Sciences, GSP-105, 603950 Nizhny Novgorod, Russia

J. L. Reno is with the Sandia National Laboratories, Albuquerque, NM 87185-0601, U.S.A

II. THz. Laser samples

A number of different design types for the basic heterostructure module as well as for the cavity of THz QCL's exists. The heterostructure design employed for the THz QCL's used in this research is based on resonant LO-phonon scattering to selectively depopulate the lower radiation level, while maintaining a long upper level lifetime, see fig. 1 [4,5]. The cavity of this QCL, operating at 2.8 THz, is of the metal-metal type, fabricated using a copper-to-copper thermo-compression bonding technique [5,6].

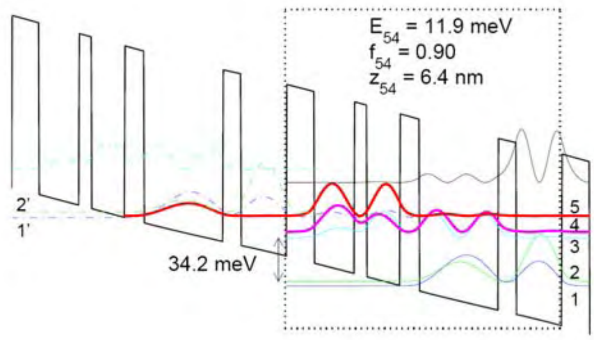

Fig. 1. Energy level scheme of the AlGaAs/GaAs heterostructure module. Lasing at about 2.8 THz occurs between levels 5&4

The advantage of such a metal-metal type of waveguide structure is two-fold. First of all, a better heat contact of the active region with the cold plate can be obtained. Secondly, and most important, the optical mode remains confined to the active region of the QCL. This is in contrast with the Semi insulating (SI) surface plasmon cavity, where a considerable part of the laser mode occurs in the non-active GaAs substrate. The active, MBE grown, region in both cases is about 10 μm thick whereas the SI substrate is 200-300 μm thick. (see fig.'s 2 and 3).

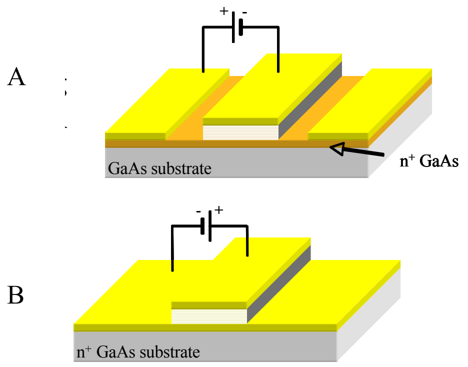

Fig. 2. Schematics of the semi-insulating surface plasmon waveguide (A) and the metal-metal waveguide (B)

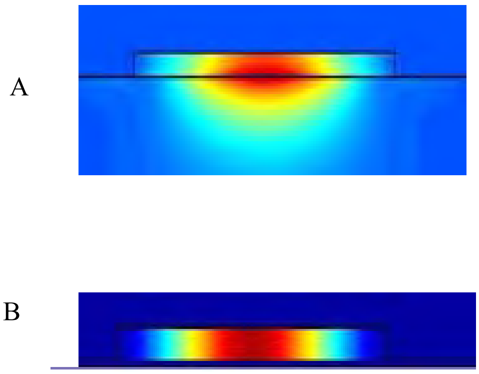

Fig. 3 Schematics of the transverse optical mode patterni n A: the semi-insulating surface plasmon waveguide, and B: the metal-metal waveguide

This optimum overlap of optical field and gain volume results in a consistently lower threshold gain for the metal-metal cavity than for the surface plasmon cavity for laser frequencies in the 1 – 7 THz range [7]. This enables a larger reduction of the active volume for the metal-metal cavity than for the SI surface plasmon cavity. As the thickness of the active region is set by the MBE growth limitations to be about 10 μm, a reduction in active volume means a reduction of width x length of the laser bar. This leads to a proportional reduction of the threshold electrical excitation power of the laser. In view of the need for cryogenic cooling of these THz QCL's, minimizing the heat load of the laser is of crucial importance. Especially for its use as local oscillator for heterodyne detection in space applications, CW operation with the lowest possible cooling budget is required.

In fact, for the smallest metal-metal cavity QCL on which we report here, with dimensions of 10 x 25 x 670 μm^3, CW operation at a record cold plate temperature of 97 K has been observed [5].

In figure 4 the I-V curve at T=7K is shown, together with the optical emission power as a function of the driving current for various cold plate temperatures. The threshold current at T = 7K is 60 mA@ 12V, leading to a minimum electrical input power of 720 mW. Strong and stable CW laser emission occurs for an electrical excitation power of only 1W! At liquid Nitrogen temperature (T=77K) an output power of 400 μW is realised with an input power of 1.2 W.

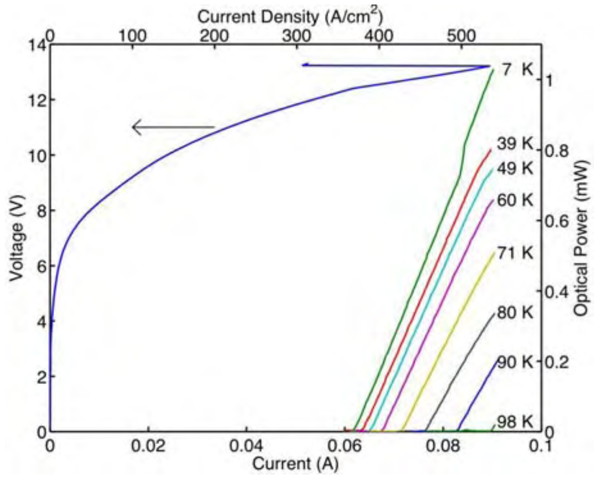

Fig. 4. I/V curve and I/L characteristics as a function of cold plate temperature of a 10 x 25 x 670 μm^3 laser operating in CW mode at 2.8 THz

The spectra presented in Fig.5 were taken in the pulsed mode (2 ms pulse length @ 40 Hz rep. rate), but are essentially equal to those taken under CW operation. Two distinctly different emission lines (at 2.76 and 2.81 THz) are observed at low temperature for different driving currents. Their frequency difference (1.89 cm^{-1}) proves that these are two longitudinal modes originating from the same transverse mode in this 0.67 mm long cavity with an index of refraction n = 3.95.

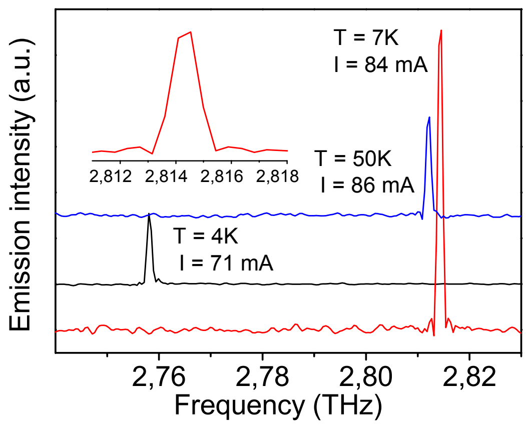

Fig. 5. Spectrum of the 10 x 25 x 670 μm^3 laser operating in CW mode.

The frequency width of the emission (see insert) is of the order of 1 GHz, and set by the resolution of the FT spectrometer. A shift towards lower frequency with increasing temperature is observed (up to about 10 GHz for T_{max} =95 K), mainly resulting from the change in dielectric constant of the active material. Apart from a small intermediate current range, the emission is single mode, and can be used for LO purposes. To illustrate the importance of the width of the cavity for (transverse) mode control, in Fig. 6 spectra for a $10 \times 40 \times 1180\ \mu m^3$ laser sample, produced from the same wafer material, are shown. In this case only for near threshold currents single mode emission is observed, whereas in general a complicated multi mode structure occurs.

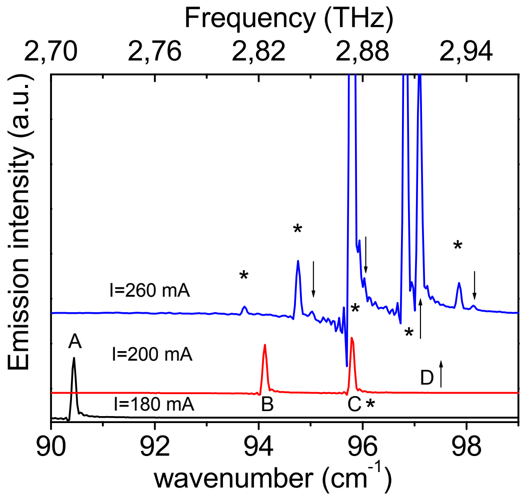

Fig. 6 . Spectra for various driving currents of the $10 \times 40 \times 1180\ \mu m^3$ sample; CW operation at 10 K Four different transverse modes (A-D) are present. Additional longitudinal modes occur for the C (*) and D(↑) transverse modes.

II. Experimental Set-up

The quantum cascade laser samples are cooled using a LHe flow cryostat (Fig. 7) with either a high density polythene - or a z-cut quartz window. With the sample near the $\Phi = 50$ mm window an effective full cone field of view of about 120^0 is obtained. The QCL is operated in the long-pulsed mode with a 250 Hz rep. rate and a 1ms pulse duration, in order to facilitate the use of a simple room temperature pyroelectric detector,

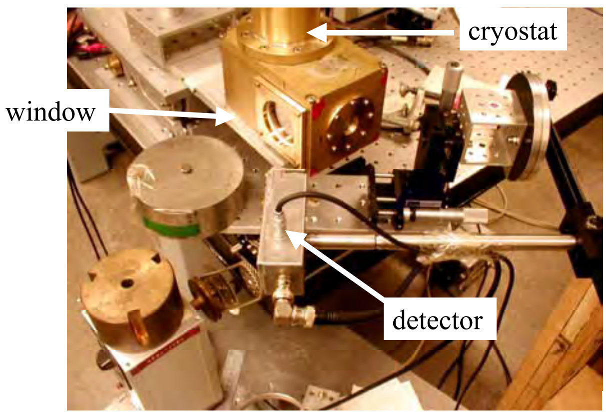

Fig. 7. Picture of the heart of the experimental set-up

and a lock-in amplifier to reduce the noise. The detector with a sensor diameter of either 2 or 5 mm, is placed in a two-axis rotation system (Fig.'s 7,8), similar to that employed in the conical section method for spherical antenna pattern measurements. The emission is monitored throughout the total solid angle of view at a constant - but adjustable - distance from the QCL. The detector movements and the recording of the signal are computer controlled. Inside the cryostat THz absorbing surfaces have been placed to avoid radiation emitted from the uncoated end facet to reflect and disturb the measured intensity pattern resulting from the forward emission.

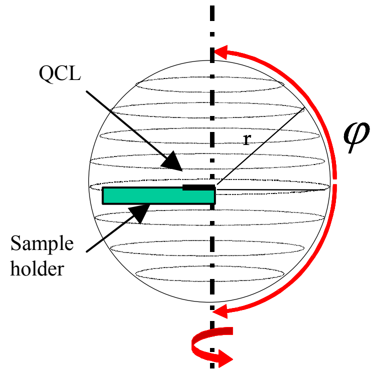

Fig. 8. Schematic view of the measurement configuration, defining the angles θ and φ

III. Results

In Fig. 9 the results of such a beam pattern measurement on the $10 \times 25 \times 670\ \mu m^3$ laser bar is shown. The detector is placed at 60 mm distance from the QCL. The results are presented in an equi-rectangular projection (θ,φ).
The emission is very small in the $\varphi < 0$ area, although the mounting of the QCL at the sample holder does not prevent radiation from the end face of the bar to reach the detector.

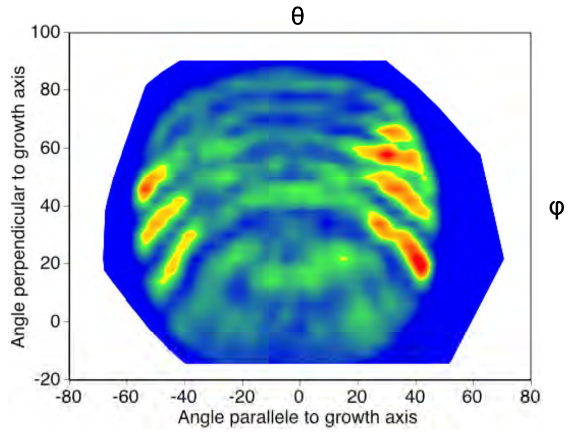

Fig. 9. Experimental beam pattern of the $10 \times 25 \times 670\ \mu m^3$ laser bar.

The beam pattern is clearly structured and not directive at all. Intensity maximums are situated on rings centered around the QCL pointing direction (θ=0°, φ=0°). The radiation emitted in that pointing direction is weak.
Preliminary experiments on laser samples with a larger length and/or width show a different, but similar structured, ring-like intensity patterns. We have carefully checked that this beam pattern is not the result of spurious reflections or to absorption or interference in the optical windows.

Beam pattern simulations based on a model for the THz emission from the front facet of a 10 µm thick metal-metal waveguide (of infinite width and length) show that the output power should change only very slowly and monotonously with the angle φ, perpendicular to the substrate [7]. Such a model clearly does not describe the emission pattern of these QCL's.

A new model is being developed to describe this peculiar angular dependence of the emission intensity of this type of sub-wavelength laser bars. The far-field pattern is calculated taking into account the emission from both the end facets and the side facets. The simulation gives a ring like intensity pattern with divergence angles fitting the experimental data.

A full description of the model will be published elsewhere.

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