The Use of Quantum Cascade Lasers as Local Oscillator for Heterodyne Detection of THz Radiation

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Many investigations in the fields of astronomy and earth observation use heterodyne detection of emission/absorption of far infrared (THz) radiation to monitor a variety of molecular species. For space borne observatories solid state THz sources as a local oscillator (LO) to pump SIS or HEB mixers are highly demanded. Until now, the highest frequency solid state LO, developed for the ESA Herschel Space Telescope, operates at 1.9 THz. Recently, Quantum Cascade Lasers working in the THz region have been developed. We will describe the properties of these very small sources, relevant for operation as LO, and show preliminary results pumping a HEB mixer.

Introduction

The development of TeraHertz technology and its use for everyday applications has been severely hindered by the lack of versatile sources. Already for many years a large variety of laser diodes for the visible and infrared wavelength region is available. However, this concept of the generation of monochromatic light using recombination of charge carriers across the band gap of a semiconductor, does not work for longer wavelengths. So, until recently one had to rely on complicated systems based on either *frequency multiplication* of high frequency microwave radiation (typically 80 – 100 GHz) or on generation of radiation at the *frequency difference* of two (VIS/NIR) diode lasers. Besides often very bulky optically pumped far-infrared lasers were utilised.
The quest for new sources has resulted in the development of two new types of THz sources. One is based on the creation of short-pulsed, and consequently very broad band, THz radiation using powerful femto-second pulses from a mode-locked Ti:Sapphire laser [1] The commonly used coherent electro-optic detection technique results in a large dynamic range and high signal to noise ratio. This type of system is widely used for THz imaging purposes. The second type of source is the THz Quantum Cascade Laser (QCL), a source of monochromatic radiation, developed very recently [2] after the example of the earlier developed (mid) infrared QCL [3].

Quantum cascade laser: basics

For the conventional diode laser the frequency is determined by the semiconductor band-gap, i.e. by the (limiting) intrinsic material properties. The QCL however, is a uni-polar device based on inter-subband transitions in heterostructures; the electrons make lasing transitions between sub-band levels within the conduction band. As the energy level splittings in heterostructures can be designed and engineered at will, in principle any lasing frequency can be realised. A basic module of a QCL consists of a number of quantum wells (typically 4-7). Stacking of up to 100 of these modules leads the "cascade" type of system: each electron injected in the first module will be used in all subsequent modules to create photons. Although the last 10 years an enormous development in the (mid) infrared QCL design and fabrication took place, it appeared to be very difficult to increase the wavelength of such devices above $\lambda \approx 25$ μm (≈ 50 meV). Two main reasons for that problem were identified. The increase of cavity losses due to free electron absorption and the smaller ratio of cavity dimension/wavelength at the one hand and the disturbing effect of the (≈ 36 meV) LO phonons on the non-radiative lifetimes of closely spaced energy levels, at the other hand.

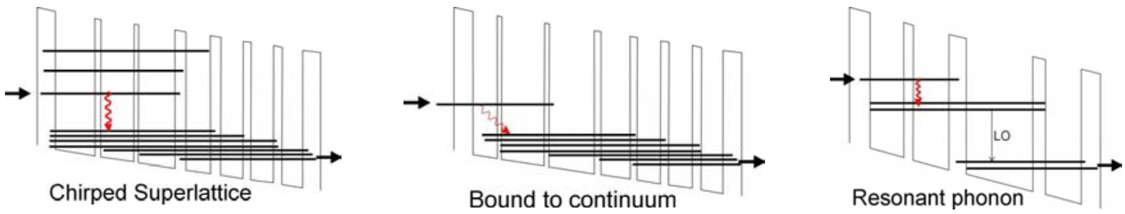
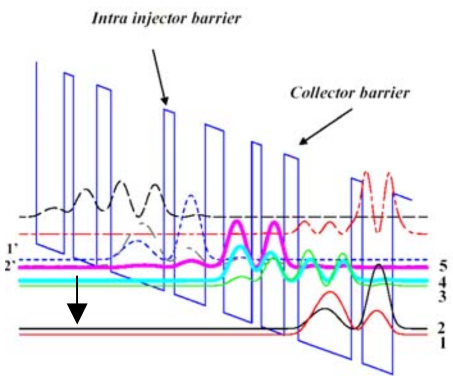


Fig. 1. Three different types of basic level schemes used for THz QCL's.

At present QCL's emitting in the 2.1 – 4.6 THz range have been reported, based on different design types for the basic heterostructure module (fig. 1) [2,3,4,5]. All aim at efficient injection of electrons in, and long lifetime of, the upper laser level, short lifetime of the lower laser level, that is, efficient removal of electrons from that level, and blocking of non-radiative relaxation paths for the electrons (parasitic current paths).



Resonant LO-phonon coupling between levels 3 and 2, together with the coupling between levels 3 and 4 results in a very short lifetime of the lower laser level 4.

Fig. 2. Design of a 2.7 THz QCL based on LO-phonon depletion of the lower laser level (4). [7]

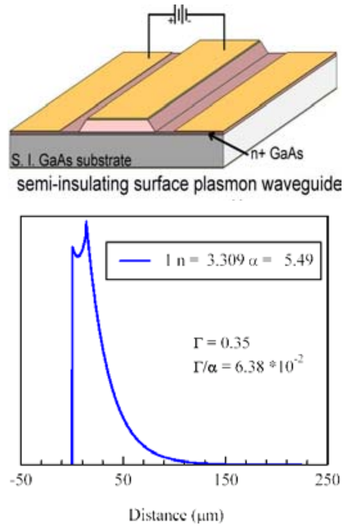


Fig.3 Shape of a "surface plasmon" waveguide and the optical mode profile for the QCL design shown in Fig. 2

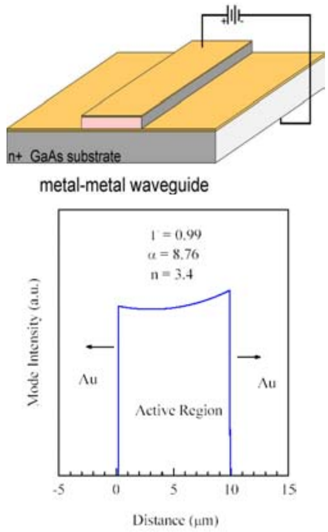


Fig 4. Shape of the "metal-metal" waveguide and the optical mode profile for the QCL design shown in Fig. 2

The devices are MBE grown in the AlGaAs/GaAs material system, and shaped in active bars with typical length and width of 1-2 mm and 25-200 μm respectively (Fig's. 3,4). The excitation current is injected through a metal top electrode and collected at a "bottom" electrode. Two different types of waveguide are used. In the "surface plasmon" waveguide, the bottom electrode is a thin, highly doped layer in-between the active region and the S.I. GaAs substrate. The optical mode extends into the non-active substrate (Fig. 3). In the "metal-metal" waveguide, the bottom electrode is a metal layer, and consequently the optical mode is confined to the small area between the two electrodes (Fig. 4), resulting in an improved overlap between mode and active region (Γ), at the cost of larger waveguide loss (α)[8]. Both types of waveguide are compatible with the TM polarisation of the intersubband transitions.

Quantum cascade laser: properties

We have studied QCL structures based on longitudinal-optical-phonon scattering for depopulation, with a metal-metal cavity, and designed for CW operation at 2.8 THz. In Fig. 5 the I-V curve of a 25 μm wide waveguide cavity is shown, together with the current dependent emission intensity. The laser action stops at the voltage (≈ 14V) where the differential resistance changes abruptly. The total maximum power under CW operation at T = 15 K is about 1 mW at an electrical input power of 2 W.

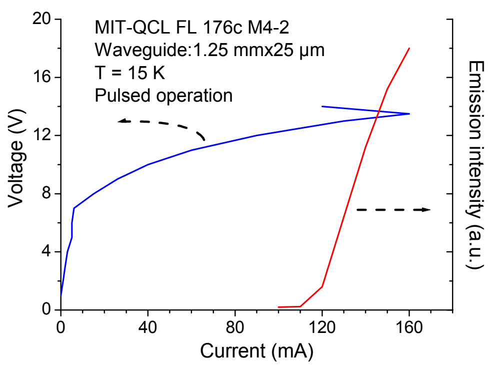


Fig. 5. I-V and L-I characteristics of 2.8 THz QCL with 1.25 mm x 25 μm cavity dimensions.

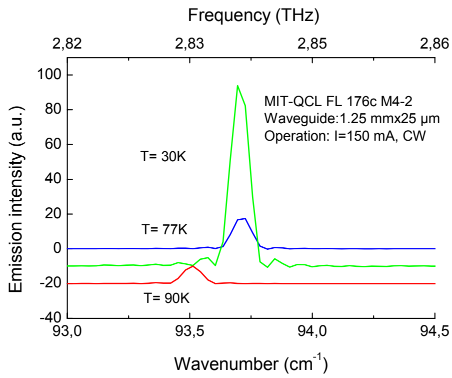


Fig. 6. Temperature dependence of emission spectrum of 25 μm wide cavity sample.

In Fig. 6 the spectrum of this laser sample is shown as a function of temperature under CW operation. A single (longitudinal) mode behaviour is observed, independent of current and temperature up to T = 90K! Towards higher temperatures the intensity drops and the frequency shows a decrease of about 10 GHz due to the temperature dependence of the dielectric constant. In Fig. 7 the low temperature spectrum of a sample from the same wafer, but with a cavity width of 40 μm, can be seen to be different. A number of

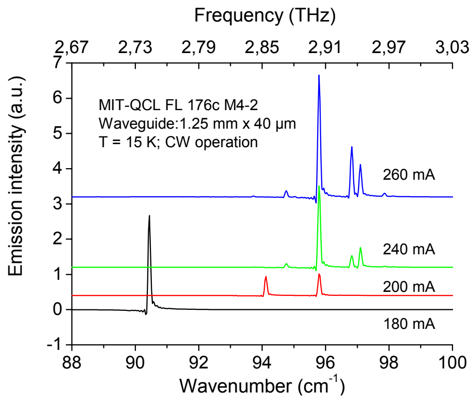


Fig.7. Current dependence of emission spectrum of 40 μm wide cavity sample.

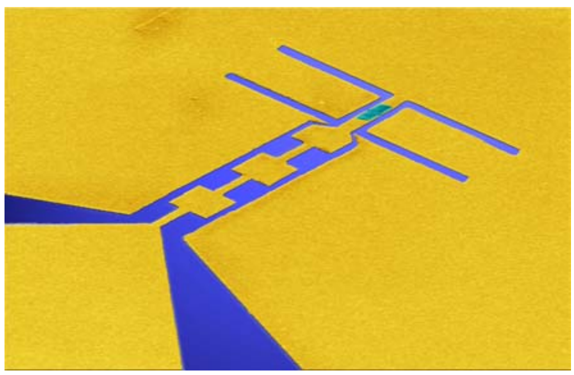


Fig. 8 Photo of the antenna coupled Hot Electron Bolometer

different transverse (and longitudinal) modes occur as a function of driving current and temperature. The overall spectrum shows that the gain width is about 8 cm^{-1}.

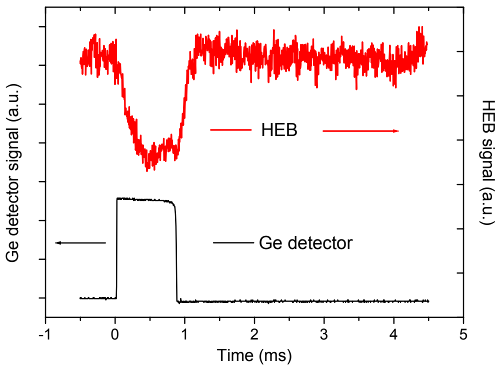


Fig. 10. Current response of the HEB (upper curve) and response of the Ge detector (lower curve) on the long pulsed 2.8 THz QCL

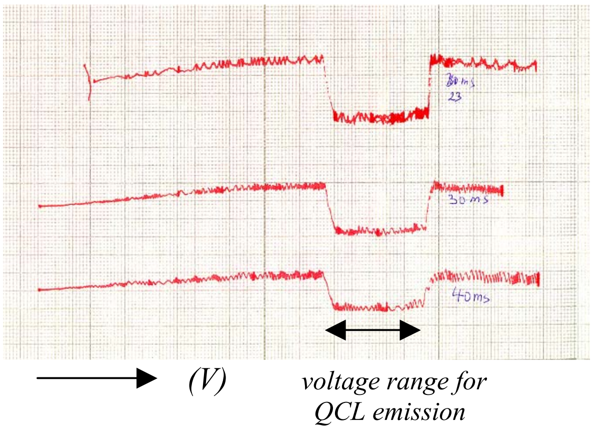


Fig. 11. Current response of the HEB detector as a function of driving voltage(current) of QCL in pulsed operation for different pulse duty cycles.

A first attempt has been undertaken to use the (25 μm) single mode laser to pump the HEB mixer shown in Fig. 9. Although the antenna for this particular HEB was designed for 1.9 THz, a clear response of the mixer was observed as can be seen in Fig. 10, where the time resolved response of both a Ge:Ga monitor detector and the HEB are shown. In Fig. 11 the response of the HEB as a function of the driving voltage of the pulsed QCL is shown; only in the voltage range where laser action occurs, a response is observed. These traces were recorded with a pen-recorder with a long time constant, so the signal is proportional to the *averaged* optical power. The time interval between pulses decreases from 40 ms for the lower trace to 23 ms for the upper trace. The resulting increase of the average power is clearly reflected in the increasing amplitude of the HEB response. In the immediate future experiments will be started to determine accurately the beam profile of the QCL and to couple more efficiently the radiation into the HEB, in order to measure the noise temperature.

References

[1] P.Y. Han and X.-C. Zhang , "Free-space coherent broadband terahertz time-domain spectroscopy," Measurement Science and Technology, **12**, 1747–1756 (2001).

[2] R. Köhler, A. Tredicucci, F. Beltram, H. E. Beere, E. H. Linfield, A. G. Davies, D. A. Ritchie, R. C. Iotti, and F. Rossi, "Terahertz semiconductor-heterostructure laser", Nature London 417, 156, 2002.

[3] J. Faist, F. Capasso, D.L. Sivco, C. Sirtori, A.L.. Hutchinson, A.Y. Cho, „Quantum Cascade Laser", Science 264(1994) 207

[4] G. Scalari, L. Ajili, J. Faist , H. E. Beere, E. H. Linfield, D. A. Ritchie , A. G. Davies, „Far-infrared (λ≈ 87 μm) bound-to-continuum quantum-cascade lasers operating up to 90K.", Appl. Phys. Lett. 82 (2003) 3165

[5] B.S. Williams, H. Callebaut, S. Kumar, Q. Hu, J.L. Reno, "3.4 THz quantum cascade laser based on longitudinal-optical-phonon scattering for depopulation", Appl. Phys. Lett. 82(2003)1015

[6] R.. Köhler, A. Tredicucci, C. Mauro, F. Beltram, H. E. Beere, E. H. Linfield, A. G. Davies, D. A. Ritchie, "Terahertz quantum-cascade lasers based on an interlaced photon-phonon cascade", Appl. Phys. Lett. 84(2004)1266

[7] M. S. Vitiello and G. Scamarcio (University of Bari) Private communication

[8] B.S. Williams, S. Kumar, H. Callebaut, "Terahertz quantum-cascade laser at λ≈ 100 μm using metal waveguide for mode confinement", Q. Hu, J.L. Reno, Appl. Phys. Lett. 83(2003)2124.