Terahertz Quantum-Cascade Lasers: Time Domain Spectroscopy and Micro Cavity Effects

J. Darmo[a], G. Fasching[a], A. Benz[a], J. Kröll[a], M. Martl[a], D. Dietze[a], S. Barbieri[c], C. Sirtori[c], A.M. Andrews[b], W. Schrenk[b], G. Strasser[b], K. Unterrainer[a,b]

[a] Institute of Photonics, Vienna University of Technology, Vienna, A-1040, Austria
[b] Center for Micro&Nanostructures, Vienna University of Technlogy, Vienna, A-1040, Austria
[c] Matériaux et Phénomenes Quantique Laboratories, Université Paris 7, Paris, F 75205 France

***Abstract*—. We have combined few-cycle THz spectroscopy with quantum cascade technology. This combination allows to perform unique THz time-domain measurements of THz-QCLs. By coupling the few-cycle THz pulse into the waveguide of the QCL, the processes within the active zone can be probed. This gives direct information regarding the energy, dynamics and coherence of transitions in the QCL structure. In addition, we will present micro-cavity quantum-cascade lasers emitting in the THz region. Strong mode confinement in the growth and in-plane directions are provided by a double-plasmon waveguide. We observe whispering-gallery modes and the threshold currents are smaller than from Fabry-Perot cavities; In the detailed study of the emission we were able to observe dynamical frequency pulling effects.**

I. Introduction And Background

TERAHERTZ quantum cascade laser (THz-QCL) is a perspective source of radiation enabling the terahertz frequency range for sensing applications in material production, security and medicine. Comprehensive knowledge and deep understanding of processes and phenomena taken place in the active region of THz-QCL is inevitable for their further improvement with respect of maximum operation temperature, pulsed operation, and mode-locking perspective.

We use a terahertz time-domain spectroscopy technique to access the spectral gain curve of THz-QCLs in both regimes below and above threshold. We have focused on the bound-to-continuum design of the active region of THz-QCLs. In principle, the chirped superlattice of the bound-to-continuum design gives a rise to two or more subbands with a plethora of energy states in contrast to the quite simple energy level situation of the resonant-phonon depopulation scheme. Those states can contribute significantly to absorption within the active region thus strongly modifying the performance of the laser.

II. Time-Resolved Results

The objects of this study are THz-QCLs with a band-to-continuum design of the active region [1]. The lasers have been processed with a surface-plasmon waveguide to a Fabry-Perot type optical resonator. The used terahertz time-domain spectroscopy set-up employs electro-optic detection of the instantaneous THz electric field [2].

Figure 1 shows a typical form of the optical gain in the THz-QCL driven 20% above the threshold current density. The gain is peaked at about 2.0 THz as expected from the design, but a non-negligible gain in the whole frequency range of 2.0 – 3.0 THz is obtained unexpectedly. The low frequency part of the spectrum is dominated by broadband loss typical for free carrier induced absorption [2,3]. The close inspection of the refractive index data reveals two important facts: First, the shape of the refractive index modulation is typical for optical gain [1]. Second, there are two distinct frequencies at which we observe optical gain. The main optical transition is located at the designed 2.04 THz and the second weaker optical transition is at 1.75 THz. We have performed calculations of the absorption spectrum to find the origin of the unexpected optical transition at 1.75 and the gain between 2.0 and 3.0 THz, respectively. The simulation strongly suggests parasitic optical transitions between the lower lasing level and states in the injector region.

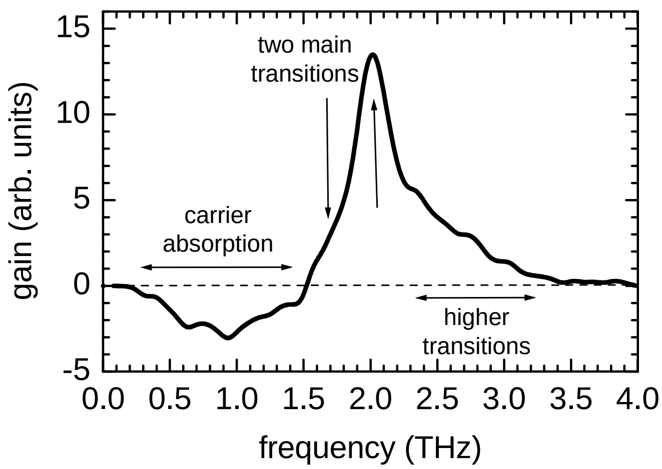

Fig.1: An example of the gain curve measured for THz-QCL.

We have performed a similar study on a range of THz-QCL designs for different emission wavelengths. An extra effort was put into an active region designed to increase the spectral gain width. The bound-to-continuum design provides quite large flexibility in the target emission wavelength. Multifrequency operation, however, requires including several different sub-region and thus the gain for the individual emission lines decreases. In addition, different wavelengths need different waveguide dimensions, so propagation losses become a strong function of frequency. A careful trade-off is required between the total size of the active region of the THz-QCL and the number of subsections.

Our experimental results on multicolor THz-QCLs also bring another problem to our attention which is the electrical and optical coupling between individual gain sections

978-1-4244-2120-6/08/$25.00 ©IEEE.

designed for different wavelengths.

III. THz QCL Microcavities

Beside the proper design of the intersubband states waveguiding plays an important role to achieve lasing in the THz frequency range.

One very interesting way to confine THz is the use of circular shaped micro resonators. The reduction of the cavity volume V towards (lambda/n)^3, where lambda and n are the emission wavelength and the effective refractive index has several implications on the emission characteristics and performance of the THz QCLs. We observed lasing from micro devices with a radius as small as 30 µm. The smallest devices exhibit stable single-mode emission in pulsed- and continuous wave (cw) operation. The threshold current is reduced and the maximum operating temperature is increased compared to larger devices. We will also report on micro ring THz QCLs and gain pulling effects [1,2].

Photonic crystals (PCs) offer another possibility to confine THz and also to control the dispersion. The use of photonics crystals for THz QCLs has two major advantages. QCLs are unipolar devices therefore no increased surface recombination currents will occur due to the increased surface. THz PCs also profit from the large wavelength which allows the use of standard optical lithography and reduces the effects of scattering loss due to processing imperfections [3]. Our PCs consist of a triangular lattice of quantum cascade rods surrounded by air to achieve a large refractive index contrast. This leads to a large band gap and a strong overlap of the optical mode with the pillars. For the vertical confinement and current supply a double-metal waveguide is used. We will report on the emission spectra, output characteristics, and the PC dispersion.

References

[1] Ch. Worrall, J. Alton, M. Houghton, S. Barbieri, H.E. Beere, D. Ritchie, and C. Sirtori, “Continuous wave operation of a superlattice quantum cascade laser emitting at 2 THz,” *Optics Express*, 14, 2006, pp. 171–181.

[2] J. Kröll, J. Darmo, S.S. Dhillon, X. Marcadet, M. Calligaro, C. Sirtori, and K. Unterrainer, “phase-resolved measurements of stimulated emission in a laser,” *Nature*, 449, 2007, pp. 698-701.

[3] J. Kröll, J. Darmo, K. Unterrainer, S.S. Dhillon, C. Sirtori, X. Marcadet, and M. Calligaro, “Longitudinal spatial hole burning in terahertz quantum cascade lasers,” *Appl.Phys. Lett.* 91, 2007, 161108.

[4] G. Fasching et al., “Sub-wavelength microdisk and microring terahertz quantum-cascade lasers“, IEEE J. Quantum. Elect. 43, 687 (2007).

[5] A. Benz, G. Fasching, Ch. Deutsch, A. M. Andrews, K. Unterrainer, P. Klang, W. Schrenk and G. Strasser, “Terahertz photonic crystal resonators in double-metal waveguides”, Opt. Exp. 15, 12418 (2007).

978-1-4244-2120-6/08/$25.00 ©IEEE.