Mode Degeneracy of "Single-Mode" Whispering-Gallery Terahertz Quantum Cascade Lasers

G. Fasching[1,2], V. Tamošiūnas[4], A. Benz[1], A. M. Andrews[1,2,3], Ch. Deutsch[1], R. Zobl[3], W. Schrenk[2,3], G. Strasser[2,3], and K. Unterrainer[1,2]

[1] Photonics Institute, Vienna University of Technology,
Gusshausstrasse 27-29, 1040 Vienna, Austria

[2] Centre for Micro- and Nanostructures, Vienna University of Technology,
Floragasse 7, 1040 Vienna, Austria

[3] Solid-State Electronics Institute, Vienna University of Technology,
Floragasse 7, 1040 Vienna, Austria

[4] Semiconductor Physics Institute, A.Gostauto 11, 01108 Vilnius, Lithuania

We present whispering-gallery terahertz quantum-cascade lasers with either "single-mode" or "double-mode" emission depending on the rotational symmetry of such resonators. Strong mode confinement in the growth and in-plane directions are provided by a double-plasmon waveguide and due to the strong impedance mismatch between the gain material and air. These ultra-compact devices exhibit increased temperature performance up to 95 K in continuous-wave mode operation and threshold currents as low as 13.5 mA. Finite-difference time-domain calculations were performed to obtain the emission spectra from such microdisk terahertz quantum-cascade lasers.

Introduction

Optical microcavities allow to confine light to extremely small mode volumes by resonant recirculation. The terahertz (THz) frequency range is very attractive to study cavity effects, as standard fabrication processes allow to realize chip based cavities on the micrometer scale with a surface roughness well below λ/30.

In recent years a great deal of research has been dedicated to realize quantum-cascade lasers (QCLs) based on Fabry-Pérot resonators emitting in the historically underdeveloped frequency region of 1 – 10 THz (30 – 300 µm) [1] – [4]. THz QCLs can be used in a wide field of applications including imaging, spectroscopy and sensing. Beside the proper design of the intersubband states waveguiding plays an important role to achieve lasing in the THz frequency range. We have recently demonstrated the first double-metal microdisk and microring QCLs operating in the THz frequency region [5] and also very recently the first single-mode emitting microdisk lasers [6].

In this contribution we present the results of our investigations on ultra-small mode volume THz QCLs based on whispering-gallery modes (WGMs) showing high temperature performance and "single"- as well as double-mode emission.

Sample Design and Fabrication

The band structure design of the $Al_{0.15}Ga_{0.85}As$/GaAs laser structure is based on the four-quantum-well THz QCL scheme introduced by Williams [4]. It combines resonant tunneling and fast depopulation of the lower laser level by the use of resonant longitudinal-optical (LO) phonons. Although the lasing transition is spatially vertical a long upper laser level lifetime of more than 5 ps is achieved.

The heterostructure was grown by molecular-beam epitaxy on a semi-insulating GaAs substrate with 271 cascaded modules resulting in a thickness of the grown laser structure of 15 µm. The QCL devices were processed into a double-metal configuration, which causes a high modal confinement in vertical direction as well as a high lateral confinement due to the semiconductor-air impedance mismatch and drastically reduces the free carrier losses compared to single-plasmon THz QCLs. Wafer pieces of the MBE-grown material and of a n^+ GaAs substrate were covered with Ti/Au. After aligning each GaAs substrate piece upside down on the metallized surface of the laser material, the samples were bonded at 330 °C for 30 min under constant pressure in a commercial wafer bonder. After removing the substrate and the $Al_{0.55}Ga_{0.45}As$ etch stop layer of the MBE-grown material, the Ti/Au top contact layers were deposited by sputtering. The contact layers as a self-aligned etch mask and an inductively coupled $SiCl_4/N_2$ plasma (ICP) were used to etch down the active region to the wafer-bonded Ti/Au layers. This resulted in perpendicular and smooth resonator boundaries with metal confinement over the whole gain medium as shown in Fig. 1. After soldering the chip onto a copper plate and wire bonding, the devices were mounted on the cold finger of a helium-flow cryostat.

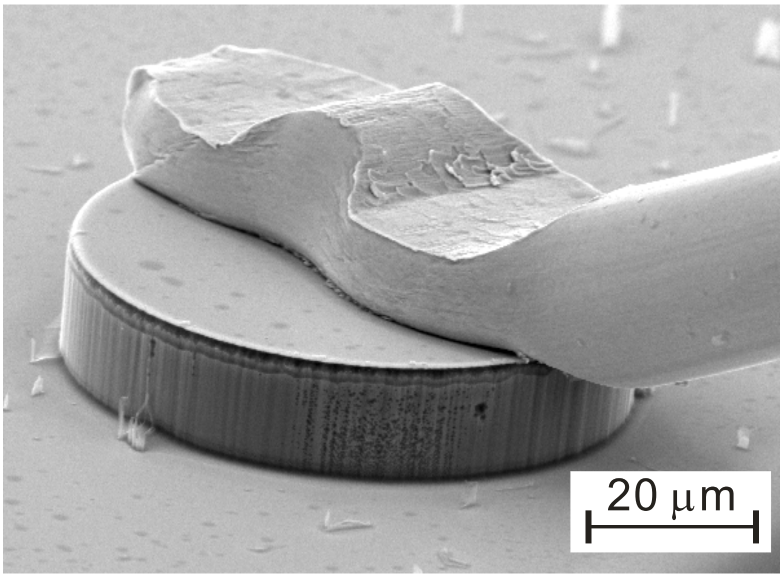

Fig. 1: Scanning electron micrograph (SEM) image of a bonded double-metal microcavity with a radius R_{out} = 35 µm and a height H = 15 µm.

Results

Simulations

A finite-difference time-domain (FDTD) method [8] is widely used to simulate the interaction of electromagnetic waves and semiconductor devices and can be efficiently employed to simulate QCLs. In this contribution, we present results of 3-D FDTD simulations of disk-shaped THz QCLs with a diameter of R = 35 µm and a height h = 15 µm. FDTD simulations of multi-mode emitting microcavities can be found in [9], [10]. Full 3-D simulations are employed to obtain the expected spectrum of the device. 350 ps of wave propagation within the resonator is simulated. The Yee cell size is set to 1.4 µm and the Courant number to 0.5 during the simulation. The average relative dielectric constant of the $Al_{0.15}Ga_{0.85}As/GaAs$ material was set to $\varepsilon = 13$ during the FDTD simulations. The obtained time-domain data from the last 233 ps is reprocessed using an integrated discrete Fourier-transform (DFT) algorithm. Only the amplitude values of the electric field component $|E_z|$ parallel to the growth direction near the bottom contact of the resonator are recorded in order to reduce the amount of computations and taking into account the selection rules. The maximum values of the amplitude are collected at each frequency to obtain the spectrum depicted in Fig. 2(a). The calculated mode spectrum exhibits a single cavity mode at 2.767 THz which is very close to the experimentally observed "single-mode" emission at 2.806 THz.

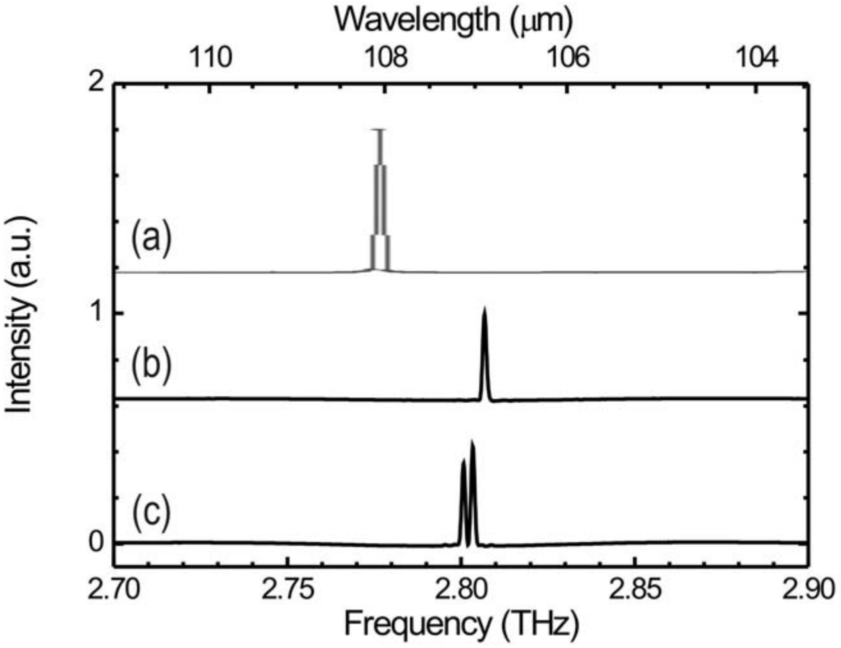

Fig. 2: (a) Simulated WGM and (b), (c) measured "single"- and double-mode emission of a microcavity THz QCL as shown in Fig. 1.

Measurements

The emission spectra were recorded using a nitrogen-purged Fourier transform infrared (FTIR) spectrometer. The spectra were measured in linear scan mode with a resolution of 0.03 cm^{-1} (0.9 GHz). The spectrometer is equipped with a 4.2 K Si bolometer. The emission spectra were measured using 3 ms long pulses with a repetition rate set to 3.33 kHz. The continuous-wave (cw) spectra of the microcavity lasers were recorded with a resolution of 0.125 cm^{-1} (3.75 GHz) using a standard DC source.

The THz QCL microcavities provide a stable "single-mode" in pulsed-mode operation as shown in Fig. 2(b) with a threshold current of 13,5 mA as well as cw operation which is highly desirable for certain applications like local oscillators. The metallic waveguide is superior to the pure dielectric waveguides with respect to heat transfer and loss for increasing wavelengths. Although the maximum achieved temperature in pulsed-mode operation is quite comparable for microdisks with different device radii, the maximum temperature in cw operation strongly increases with decreasing device radius up to a maximum heat-sink temperature of 95 K [10]. This fact can be clearly attributed to a better thermal management for smaller devices which have the same dynamical current range as the larger ones. This demonstrates that circular-shaped microcavities give the opportunity to create ultrasmall devices with extremely low operational current and therefore low electrical power dissipation which enhances the cw performance.

In addition we have observed a closely spaced double-mode emission with a spacing below 4 GHz as shown in Fig. 2(c) from other microcavities with the same cavity dimensions under the same measurement conditions. WGMs possess a natural two-fold degeneracy due to the two possible directions of propagation (clockwise and counterclockwise). Imperfections inside or at the surface of high quality factor *Q* resonators can yield to scattering causing mode coupling of the two counterpropagating modes resulting in a mode-doublet [11]. For our cavities we broke the rotational symmetry of some of the resonators due to not perfectly centered bond wires at the top contact. This influences the phase conditions of the modes leading to a lifting of the natural two-fold degeneracy of the WGMs causing this double-mode emission [10]. In general, the ability to controllably change the field distribution inside the microcavity would lead to a controllable change of the emission frequency as well as the cavity *Q*.

References

[1] J. Faist, et al.: “Quantum cascade laser,” *Science*, vol. 264, pp. 553–556, 1994.

[2] R. Köhler, et al.: “Terahertz semiconductor heterostructure laser,” *Nature* (London), vol. 417, pp. 156-159, 2002.

[3] G. Scalari, et al.: “Far-infrared (λ ~ 87 µm) bound-to-continuum quantum cascade lasers operating up to 90 K,” *Appl. Phys. Lett.*, vol. 82, pp. 3165-3167, 2003.

[4] B. S. Williams, et al.: “3.4-THz quantum cascade laser based on scattering for depopulation,” *Appl. Phys. Lett.*, vol. 82, pp. 1015-1017, 2003.

[5] G. Fasching, et al.: “Terahertz microcavity quantum-cascade lasers,” *Appl. Phys. Lett.*, vol. 87, p. 211112, 2005.

[6] G. Fasching, et al.: “Sub-Wavelength Terahertz Quantum-Cascade Laser Resonators (Presented Conference Paper Style), *presented at CLEO06, Los Angeles, CA, May 21-26, 2006, Paper CTuT3*.

[7] A. Benz, et al.: “The influence of doping on the performance of terahertz quantum-cascade lasers,” *Appl. Phys. Lett.*, vol. 90, p. 101107, 2007.

[8] A. Taflove, Computational Electrodynamics: The Finite-Difference Time-Domain Method, Boston, USA: Artech House, 1995 (and references within).

[9] G. Fasching, *et al.*: “Microcavity terahertz quantum-cascade laser,” *SPIE-Int. Soc. Opt. Eng, vol. 6010, p. 601006, 2005.*

[10] G. Fasching, et al.: “Sub-Wavelength Microdisk and Microring Terahertz Quantum-Cascade Lasers,” *IEEE J. Quantum Electron.*, vol. 43, pp. 687-697, 2007.

[11] D. S. Weiss, et al.: “Splitting of high-Q Mie modes induced by light backscattering in silica microspheres,” *Opt. Lett.*, vol. 20, pp. 1835-1837, 1995.