Terahertz Quantum-Cascade Lasers in a Magnetic Field

V. Tamošiūnas, R. Zobl, G. Fasching, J. Ulrich, G. Strasser and K. Unterrainer
Institute of Solid State Electronics, TU Vienna, Austria

R. Colombelli, C. Gmachl, L.N. Pfeiffer and K.W. West
Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974

F. Capasso
Harvard University, Division of Engineering and Applied Sciences, Cambridge, MA 02138

Terahertz quantum-cascade lasers (QCLs) are coherent sources of far-infrared radiation based on semiconductor heterostructures. Operation of QCLs in the Terahertz range of the electromagnetic spectrum was demonstrated just recently and the further improvement of the THz QCLs is a challenge for several reasons related to the intersubband population dynamics and to the waveguide properties. Electron-electron and interface roughness scattering represent the main scattering mechanisms at low temperatures in this range of intersubband energies. They lead to fast carrier relaxation and they counteract population inversion. It was proposed to increase the intersubband lifetime by applying a magnetic field normal to the epitaxial layers. The additional quantization (induced by the magnetic field) of the in-plane electronic motion dramatically modifies the electron-electron scattering in the Landau-quantized energy spectrum.

In this contribution, we report on the behavior of a 4.5 THz QCL in an external magnetic field. The structure consists of 100 periods of a layer system of GaAs wells and $Al_{0.15}Ga_{0.85}As$ barriers sandwiched between two n+-doped contact layers, and it was grown on a semi insulating GaAs substrate using molecular beam epitaxy.

The system used in the emission experiments consists of a FTIR spectrometer and a 4.2 K Si bolometer. For the magnetic field measurements, the THz QCL is mounted in a magnet cryostat with two superconducting magnets. In this cryostat, detection is possible by a magnetic field tunable InSb cyclotron resonance detector, by a broadband Ga doped Ge detector, or by the external FTIR (Fig. 1).

The broadband Ge detector was used to obtain the laser intensity as a function different sample magnetic fields which is presented in Fig. 2. The laser emission intensity increases substantially for certain values of the magnetic field when compared to B = 0 T. For increasing magnetic fields we observe oscillations with a larger period. The application of a magnetic field increases the laser intensity by a factor of more than five at B = 4.2 T. This effect is understood as a consequence of the discretization of the energy spectrum. A magnetic field breaks the subbands into ladders of Landau levels with energies:

$$E_2 - E_1 = \frac{\hbar e B_N}{m^*} N$$

where E_2 - E_1 is the energy difference, $\hbar$ the Planck constant, e the elementary charge, B_N magnetic flux density , m^* effective mass, N an integer. For certain values of the magnetic field it is possible to achieve favorable conditions for fast energy relaxation in the injector and to suppress nonradiative relaxation in the active region. This leads to an increase of the population inversion and to an increase of the emission intensity.

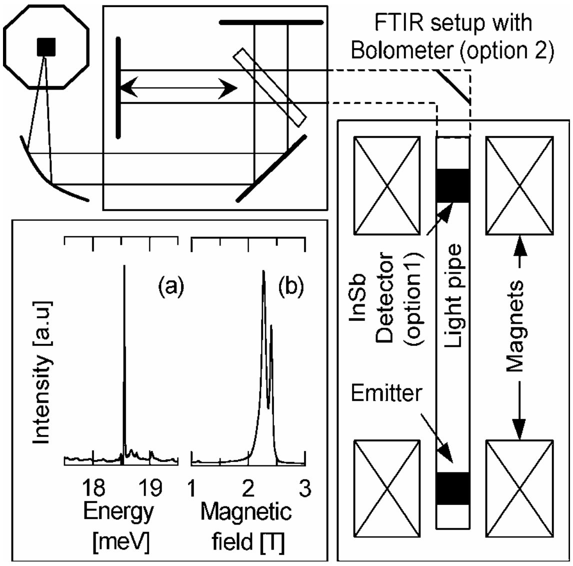

Fig. 1: Set-up for high resolution spectral measurements.
(a) High-resolution spectrum of the laser without applied magnetic field at the emitter sample.
(b) Response of the InSb detector versus applied detector magnetic field when illuminated by the THz laser.

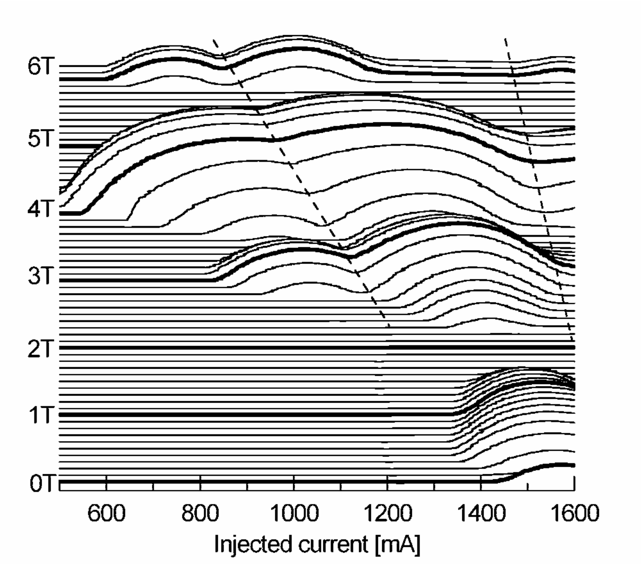

Fig. 2: Laser emission intensity as a function of the injected current at different magnetic fields applied to the sample. The pulse width was 150 ns at 90 kHz repetition rate.

Figure 3 summarizes the spectral features observed in the magnetic field. A substantial spectral shift is consistently observed in addition to a conventional Stark shift. A combination of Bloch gain, conventional intersubband gain, and many body effects like the depolarization effect can cause these emission line shifts. However, a future research is required to evaluate the possible contribution of each effect.

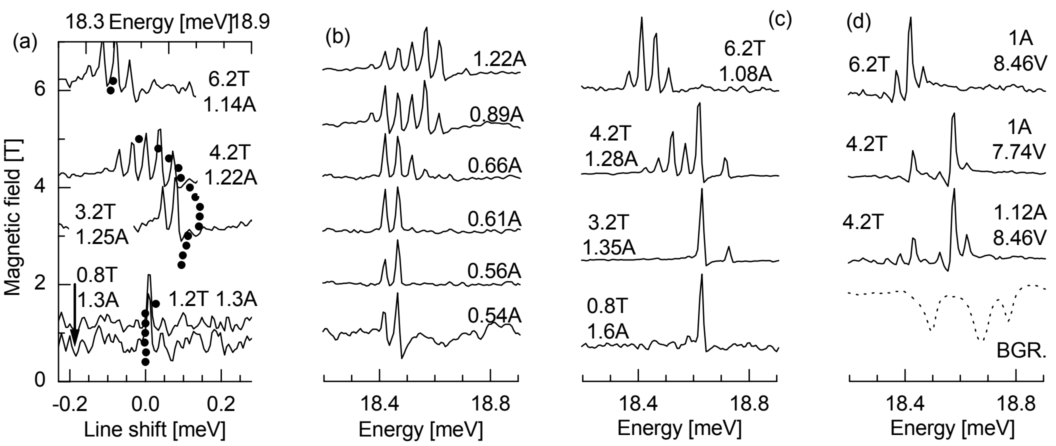

Fig. 3: (a) Frequency of the emission line vs magnetic field applied to the sample, measured by the InSb detector (dots), and high-resolution spectra measured by the external FTIR for several different magnetic fields (lines).
(b) High-resolution spectra for different injected currents at a fixed magnetic field of 4.2 T. Multimode emission and a Stark shift are observed.
(c) Constant bias voltage measurement: The measured voltage was set to 9.5 V for all measurements at a pulse length of 200 ns and at a repetition rate of 94 kHz. An additional emission line appears consistently above 18.7 meV at 3.2 and 4.2 T. The 18.65 meV emission line is not recorded due to a water absorption line.
(d) Long pulse (400 ns) measurements at 6.2 T (1 A and 8.46 V, as measured on the sample), and for 4.2 T at constant voltage and current. A background spectrum with water vapor absorption lines is also presented (BGR).

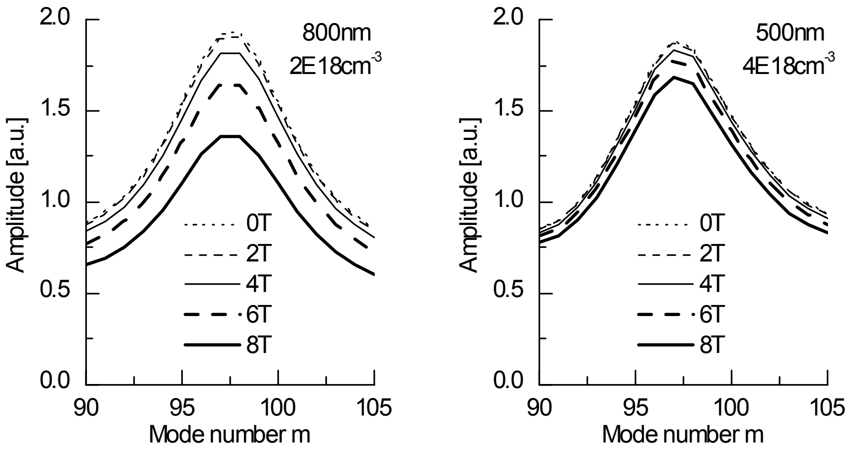

Fig. 4: Maximum amplitude versus resonator mode number simulation results for two different n+ layers.

We have employed a finite-difference time domain (FDTD) based algorithm to investigate the changes of the waveguide properties in a magnetic field. Two waveguide designs are compared in Fig. 4. A broader operating range is predicted for our waveguide design when compared the design of Ref. [1]. A predicted intensity reduction in strong magnetic fields is also consistent with the experiment.

In conclusion, we have observed a reduction of the threshold current density, a simultaneous enhancement of the laser emission intensity in a magnetic field and clear shifts of the emission spectra when the external magnetic field is applied, while operating the device at constant voltage or current. Our FDTD simulation results for the QCL waveguide are consistent with the experimentally observed reduction of QCL emission intensity.

Acknowledgement

The authors acknowledge support from the FWF (SFB-ADLIS).

References

[1] V. Tamosiunas, R. Zobl, J. Ulrich, K. Unterrainer, R. Colombelli, C. Gmachl, F. Capasso, K. West, L. Pfeiffer, Applied Physics Letters, **83**, 3873 (2003).

[2] V. Tamosiunas, R. Zobl, G. Fasching, J. Ulrich, G. Strasser, K. Unterrainer, R. Colombelli, C. Gmachl, F. Capasso, K. West, L. Pfeiffer; “Magnetic Field Effects in Terahertz Quantum Cascade Lasers”; Semiconductor Science and Technology, to be published.