2.4. Intersubband Emitters: GaAs-based Quantum-Cascade Lasers

THz quantum-cascade lasers are promising light sources for a large number of applications such as environmental analysis, diagnostics in biology as well as medicine, and imaging techniques for quality control as well as security screening. In some cases, devices with widely tunable frequency and operation above Peltier cooling temperatures are essential. These requirements have not yet been achieved for the THz spectral range so that further research efforts are necessary.

One of the controversial questions discussed in the literature concerns the impact of free-carrier absorption (FCA) on the laser performance. If there would be no significant effect of the FCA on the laser operation or the dependence of the threshold current density $j_{\mathrm{th}}(n_{\mathrm{s}})$ on sheet carrier concentration would be linear, it would not be possible to determine an upper value of n_{s} for a non-vanishing dynamical range of lasing by FCA. Therefore, we experimentally investigated $j_{\mathrm{th}}(n_{\mathrm{s}})$ and $j_{\mathrm{max}}(n_{\mathrm{s}})$, the current density for maximum laser output, for a set of THz QCLs with doping between 2.0×10^{11} cm^{-2} and 2.2×10^{12} cm^{-2} at different temperatures. The results clearly demonstrate a nonlinear behavior of both $j_{\mathrm{th}}(n_{\mathrm{s}})$ and $j_{\mathrm{max}}(n_{\mathrm{s}})$, indicating the impact of FCA on the dynamical range. At the same time, model calculations of the dielectric function of the cascade structure with different carrier concentrations in the various layers show that the optical losses and therefore j_{th} increase nonlinearly with increasing n_{s}. While the FCA determines mainly the low-temperature values of $j_{\mathrm{th}}(n_{\mathrm{s}})$ and has in addition to the gain coefficient a strong influence on the values of $P_{\mathrm{max}}(n_{\mathrm{s}})$, it does not significantly affect the temperature performance of THz QCLs.

Recently, studies of the gain recovery in quantum-cascade lasers has become of increasing interest. Since the population inversion is affected by carrier transport through the injector, the gain recovery mechanism is qualitatively different from the one in conventional lasers and is determined by the time-dependent transport of electrons through both the active regions and the injector regions connecting them. Therefore, we have started to numerically simulate the interplay between stimulated emission and carrier transport. In a first simulation of a structure with a spatially diagonal transition, the inclusion of stimulated emission following the gain-equals-loss condition leads to a redshift of the gain maximum for field strengths at which the gain would exceed the optical losses, since the carrier density in the upper laser level is reduced. Such simulations may provide useful information for the design of tunable lasers and possibly explain the failure to demonstrate laser operation in structures for which a large gain was calculated neglecting the impact of the stimulated emission on transport.

2.4.1 Effect of free-carrier absorption in THz quantum-cascade lasers

Currently, investigations of terahertz (THz) quantum-cascade lasers (QCLs) are of great interest, because of the large number of their potential applications for diagnostics in biology and medicine, analysis of trace gases, environmental analysis, communication technologies, and for security screening. Most of these applications require at least low energy consumption, high power, high brilliance, and wide-frequency tuning range. Furthermore, compact and mobile devices are desired, which exhibit lasing for temperatures above the Peltier cooling range. However, most of these requirements cannot presently be achieved.

We investigate the effect of free-carrier absorption (FCA) on the laser performance in differently doped THz QCLs based on the design introduced by S. Barbieri *et al.* [Appl. Phys. Lett. **85**, 1674 (2004)] using surface-plasmon waveguides. The sheet carrier concentration in the cascade structure is denoted by n_s. We study in particular the influence of n_s and the temperature T on the threshold current density $j_{\rm th}$, on the current density for maximum laser output $j_{\rm max}$, on the dynamical range (DR) of lasing defined by $j_{\rm th} \leq j \leq j_{\rm max}$, and on the maximum laser output power $P_{\rm max}$. We focus on three questions: (*i*) Is the experimentally observed dependence of $j_{\rm th}$ and $j_{\rm max}$ on n_s linear or nonlinear? (*ii*) Does the FCA due to LO-phonon scattering cause a linear or a nonlinear dependence of $j_{\rm th}$ on n_s? (*iii*) What is the effect of the FCA on the temperature performance of THz QCLs?

With respect to the first question about the dependence of $j_{\rm th}(n_s)$, there are two different conclusions published in the literature. Whereas H. C. Liu *et al.* [Appl. Phys. Lett. **87**, 141102 (2005)] and L. Ajili *et al.* [J. Appl. Phys. **100**, 043102 (2006)] have concluded that the FCA causes a linear dependence of $j_{\rm th}$ and $j_{\rm max}$ on n_s, A. Benz *et al.* [Appl. Phys. Lett. **90**, 101107 (2007)] have claimed that there is no significant effect of FCA. The increasing value of $j_{\rm th}$ with increasing n_s should be due to a decreasing electrical resistance of the cascade structure and the requirement of an almost constant bias for the laser threshold. Assuming that

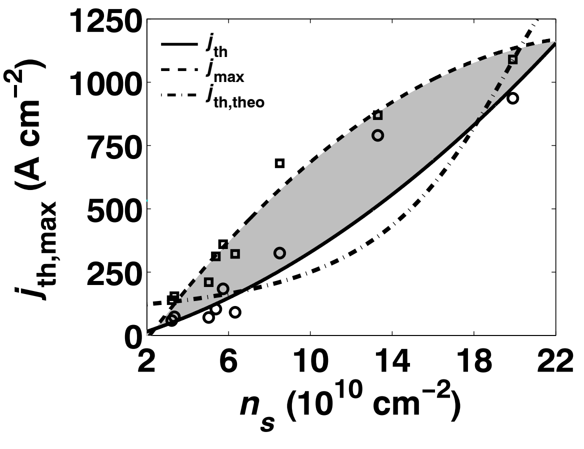

Fig. 24. Measured values of $j_{\rm th}$ (circles, solid line) and $j_{\rm max}$ (squares, dashed line) and model calculations of $j_{\rm th}$ (dash-dotted line) as function of n_s at 7 K.

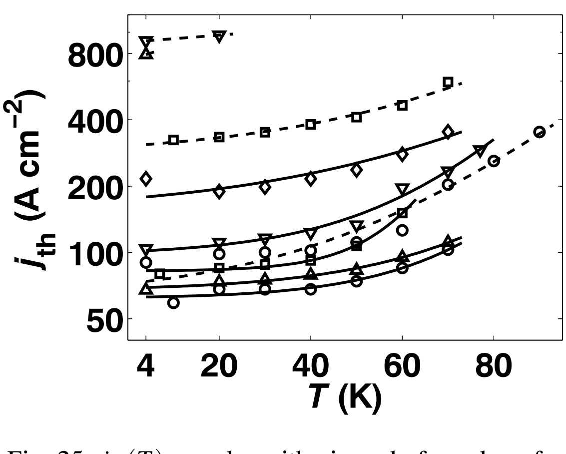

Fig. 25. $j_{\rm th}(T)$ on a logarithmic scale for value of n_s in units of 10^{10} cm^{-2}: solid lines and circles referring to 3.2, □ 3.4, △ 5.0, ▽ 5.4, as well as ◊ 5.7, dashed lines and circles 6.3, □ 8.5, △ 13.3, and ▽ 19.9.

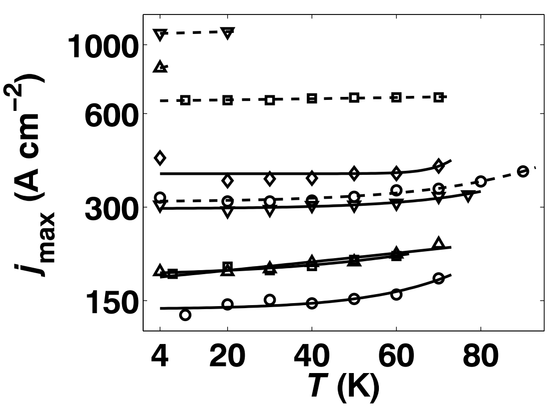

Fig. 26. $j_{\mathrm{max}}(T)$ on a logarithmic scale for differently doped THz QCLs. The symbols are explained in Fig. 25.

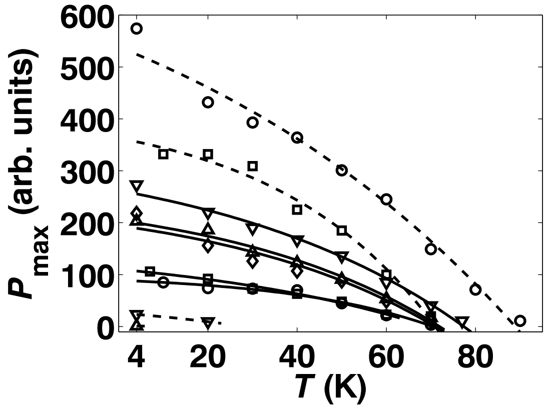

Fig. 27. $P_{\mathrm{max}}(T)$ on a linear scale for differently doped THz QCLs. The symbols are explained in Fig. 25.

j_{th} and j_{max} are linear functions of n_s or that there is no significant effect of the FCA on the laser performance, the FCA does not result in an upper value of n_s for the limit of the DR of lasing. As shown in Fig. 24, our investigations of THz QCLs over a wide range of n_s values (2.0×10^{11} cm$^{-2} \leq n_s \leq 2.2\times10^{12}$ cm^{-2}) for temperatures between 7 and 90 K demonstrate a nonlinear behavior of both j_{th} and j_{max} on n_{s}, indicating clearly the impact of the FCA on the DR of lasing.

With respect to the second question about the nonlinear dependence of j_{th} on n_s due to FCA caused by LO-phonon scattering, we have to take into account that the light of the QCLs is p-polarized and that the electric field is parallel to the growth direction of the layers. Therefore, we have to calculate the average of the inverse dielectric functions of all lasers within the QCL, weighted by the thicknesses of the corresponding layers. QCLs consist of layers with different doping levels (undoped as well as intermediately doped within the cascade structure and highly doped within the waveguides). From the nonlinear averaging, we obtain a nonlinear increase of the optical losses and therefore for j_{th} with increasing n_s. The model calculations, shown in Fig. 24, reproduce the experimental results well.

With regard to the third question, j_{th} increases, j_{max} remains almost constant, and P_{max} decreases with increasing temperature as shown in Figs. 25, 26, and 27, respectively. However, these variations are almost independent of n_s, indicating that the decreasing laser performance with increasing T is almost unaffected by FCA. The temperature dependences of j_{th} and P_{max} are caused, e. g., by the thermal depletion of the upper laser level and backfilling of the lower laser level due to LO-phonon scattering. Moreover, j_{max} is almost temperature independent, indicating that FCA has no impact on j_{max} as expected from the laser rate equations.

In summary, we have demonstrated that n_s has a strong impact on j_{th}, j_{max}, and P_{max}. The FCA determines mainly the low-temperature values of j_{th} and has a strong influence on P_{max}, while it does not significantly affect the temperature performance of THz QCLs.

(M. Giehler, R. Hey, H. Kostial, L. Schrottke, H. T. Grahn)

2.4.2 Simulation of the interplay between stimulated emission and carrier distribution in quantum-cascade lasers

Semiconductor lasers based on electron-hole recombination exhibit, for not too high intensities, a population inversion pinned at its threshold value due to the gain-equals-loss condition. This condition leads to a complete conversion of any additional pumping power into increasing laser output provided that the gain recovery can be considered to be instantaneous. For quantum-cascade lasers (QCLs), however, the population inversion is affected by carrier transport through the injector so that the gain recovery mechanism is qualitatively different from that in conventional lasers. H. Choi *et al.* [Phys. Rev. Lett. **100**, 167401 (2008)] have shown using pump-probe experiments that the gain recovery is determined by the time-dependent transport of electrons through both the optically active regions and the injector regions connecting them. As stimulated emission influences the transport through the active region, our model has been expanded by the interplay between stimulated emission and carrier transport.

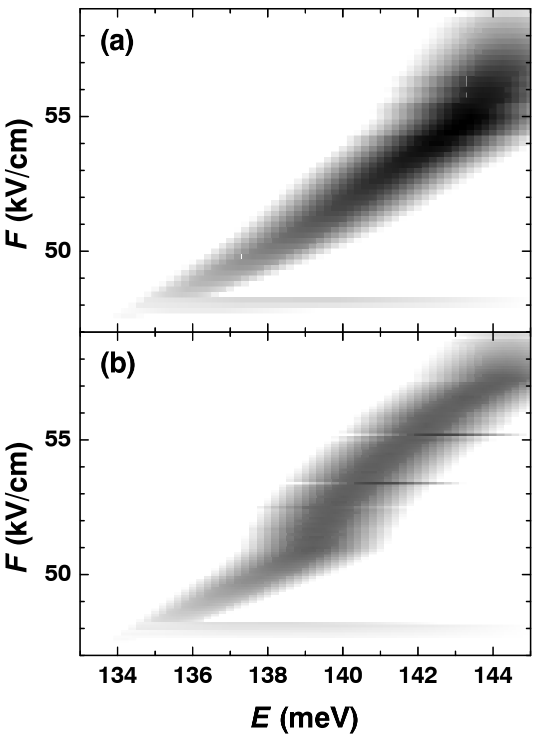

Fig. 28. Grey-scale representations of the calculated gain (a) neglecting stimulated emission and (b) including the simulation of stimulated emission. Darker areas correspond to larger gain. The grey scale is identical for both representations.

The interplay of stimulated emission and carrier transport is expected to modify the electron distribution and consequently the electrical field strength within each period so that the lasing energy may be shifted due to the quantum-confined Stark effect. This may be an essential information for the design of electrically tunable intersubband emitters. Furthermore, the extended model can simulate the influence of the gain recovery behavior due to miniband transport on the operation of QCLs. In particular, the failure of demonstrating laser operation for some designs with a large calculated gain may be explained, if the impact of stimulated emission on transport above threshold is included. For QCLs with a more complex optically active region, in which several intersubband transitions possess similar energies, the interaction of these transitions mediated by the laser field may be simulated.

The model is based on the self-consistent solution of the Schrödinger and Poisson equations using a two-band model in order to allow for non-parabolicity effects. Carrier transport is included by transitions rates $T_{ij} = \gamma_E(E_{ij})|D_{ij}|^2$ between i^{th} and j^{th} subbands with the dipole matrix element D_{ij}. The energy-dependent factor $\gamma_E(E_{ij})$ allows for the empirical treatment of transitions due to electron-phonon scattering. In order to simulate the impact of the laser field on the transport, $\gamma_E(E_{ij})$ is extended by a term for emission or absorption of photons. This term is proportional to the number of photons in the cavity modes interacting with the intersubband transition described by a Lorentzian with a broadening parameter $\Gamma = \Gamma_i + \Gamma_j$. For Γ, externally determined values may be used or the values for $\Gamma_i = \sum_j T_{ij}$ are calculated within the model. The modified transitions rates lead to a redistribution of carriers and a decrease of gain.

At the same time, the number of photons ϕ_k in the k^{th} cavity mode will increase (decrease), if the gain g is larger (smaller) than the optical losses α. Neglecting spontaneous emission, we assume $d\phi_k/dt \sim (g-\alpha)\phi_k$. The gain contribution of the transition $i \rightarrow j$ is given by $g \sim E_{ij}|D_{ij}|^2(N_i - N_j)$ with N_i denoting the carrier density in the i^{th} subband. The stationary case, which is reached when $g = \alpha$ (stimulated emission) or when all $\phi_k = 0$ (absorption), is found by the generalized self-consistent solution including these laser rate equations.

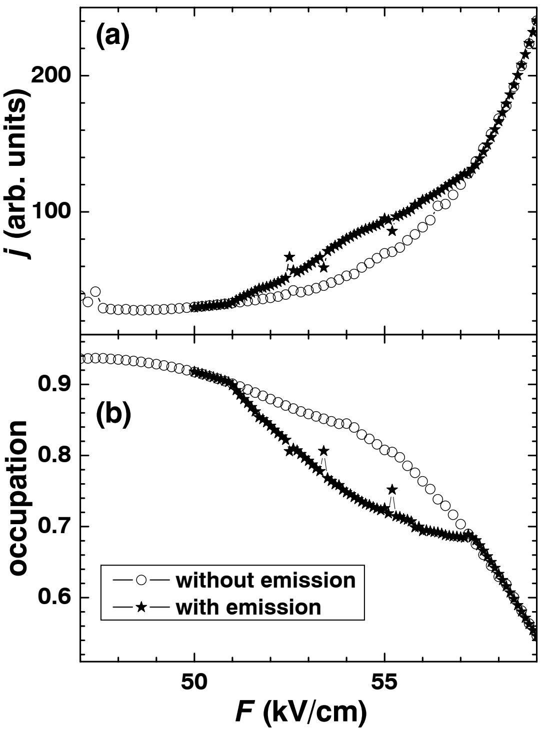

Fig. 29. (a) Calculated current density j and (b) relative occupation of the upper laser level for the diagonal transition as a function of the applied electric field F.

For a first qualitative study of the interplay between carrier transport and stimulated emission, we applied the model to a QCL design for the mid-infrared spectral region in which only one transition significantly contributes to the total gain. Furthermore, we started with a simplified version assuming a constant $\Gamma = 5$ meV for all transitions and neglecting the energy dependence of the gain. As shown in Fig. 28, the inclusion of stimulated emission leads to a redshift of the gain maximum for field strengths at which the gain would exceed the losses. The gain-equals-loss condition requires a reduction of the carrier density in the upper laser level, which is provided by the faster transition due to stimulated emission. The smaller occupation of this level leads a lower energy position. At the same time, the stimulated emission leads to an increase of the total current density as shown in Fig. 29.

Currently, the significance of calculated values for Γ instead of using fixed values is investigated using a more comprehensive version of our model. Further investigations will focus on those THz QCL designs which exhibit multiple branches in the gain characteristics in order to study the interaction between different transitions mediated by the photon field. Altogether, the goal is to find out how the extended model predicts the accurate laser energies and whether it can be used for the design of electrically tunable THz QCLs.

(L. Schrottke, M. Giehler, H. T. Grahn)