# Abstract

The large variety of applications in the terahertz (THz) frequency range, such as spectroscopy and imaging, triggered strong interest in developing powerful solid state sources for coherent THz radiation. In terms of size, output power, and efficiency, THz quantum cascade lasers (QCLs) are the devices of choice to generate such radiation. These electrically pumped semiconductor lasers are capable of delivering watt-level output power and reach maximum operating temperatures of 200 K. A major advantage of QCLs compared to standard diode lasers is that the emission frequency can be designed by engineering the semiconductor heterostructure. The state-of-the-art for realizing broadband THz gain media are QCLs with heterogeneous active regions. They rely on stacking individually designed quantum cascade structures with different emission frequencies into a single laser waveguide. Using this approach, it is possible to engineer the spectral gain profile and achieve octave-spanning laser emission. Such broadband THz QCLs can be used as tunable sources, for mode-locking, for short pulse generation, or as optical frequency combs.

The aim of this thesis was to investigate the intersubband dynamics of broadband THz QCLs and to utilize them for the generation and amplification of ultra-short THz pulses. Heterogeneous active regions offer high design freedom to control the spectral position, the bandwidth, and the flatness of the optical gain. However, additional constraints make the overall design challenging. Terahertz time-domain spectroscopy (THz-TDS) is the ideal tool to study and characterize QCLs during operation. This femtosecond laser based technique uses broadband THz pulses to investigate the sample of interest and its coherent detection scheme allows to measure the amplitude and phase of the THz field in a single scan.

The first goal of this thesis was to extend a THz-TDS system in order to study metal-metal THz QCLs. Due to the implemented improvements it is now possible to acquire time-resolved modulation signals with a signal-to-noise ratio of 40 dB and with a spectral resolution of less than 50 GHz. These advancements enabled to study the spectral gain of a heterogeneous laser as a function of the driving current and the operating temperature. The experiments revealed

that the multi-stack active region exhibits an ultra-broad gain bandwidth of 1.8 THz with a peak gain value of $\sim 10\,\mathrm{cm}^{-1}$. Furthermore, it was found that the optical gain associated with the three quantum cascade stacks, centered at 2.3, 2.7, and 3.0 THz, clamps at different driving currents and saturates to different values. This is attributed to varying pumping efficiencies of the respective upper laser states and to frequency dependent optical losses. Temperature dependent measurements showed no significant change of the cavity losses within the operating temperature range and revealed a steep decline of the intersubband gain after laser switch off. The achieved results provide valuable information for theoretical modeling and enable further improvement of heterogeneous lasers.

The second goal of this thesis was to establish a TDS based method to measure the dispersion of broadband THz QCLs as a function of bias and frequency. The group velocity dispersion (GVD) is an important parameter, particularly relevant for the frequency comb formation dynamics of THz QCLs. In this work, it was found that the GVD exhibits frequency dependent oscillations with amplitudes up to $1\times10^5\,\mathrm{fs}^2/\mathrm{mm}$ between 2.0 and 3.0 THz and strongly depends on the driving conditions of the laser. This indicates that the GVD in THz QCLs is mainly determined by the intersubband gain in the active region. The presented TDS dispersion measurements are essential to design dispersion compensation structures in order to improve the performance of THz QCL based frequency combs.

Apart from using heterogeneous THz quantum cascade structures to build broadband lasers, they are ideal candidates for the generation and amplification of short pulses. In this thesis, a broadband quantum cascade structure based THz amplifier is demonstrated. This could be realized by employing a coupled cavity device, which consists of an integrated source of coherent THz pulses and a quantum cascade amplifier section. The amplification process relies on ultrafast gain switching that is initiated by a radio frequency pulse. The sub-nanosecond long microwave pulses with peak powers up to 31 dBm are generated by an amplifier chain that was developed in this work. In addition, injection seeding permits coherent detection of the emitted THz pulse train. The presented quantum cascade devices exhibit amplification bandwidths up to 1 THz and amplification factors up to 30 dB.

The final goal of this thesis was the development of a waveguide engineering technique to control and fully suppress higher order lateral modes in broadband THz QCLs. This could be achieved by implementing lossy side-absorbers to the edges of metal-metal waveguides. The designed absorbers allowed to obtain octave-spanning laser emission centered at 2.5 THz and frequency comb operation with a bandwidth of 440 GHz. Furthermore, the absence of higher order lateral modes enabled the formation of a clean train of nearly transform-limited THz pulses with a record ultra-short pulse length of 2.5 ps. Together with the seeded bandwidth of 1 THz, this makes such devices powerful sources for TDS systems, in particular to boost the signal-to-noise ratio for frequencies above 2 THz.