Extending the spectral range of GaInAs/AlInAs/InP quantum cascade lasers by intracavity nonlinear frequency mixing

Augustinas Vizbaras[1], Robert W. Adams[2], Min Jang[2], Mikhail A. Belkin[2], Christian Grasse[1],
Gerhard Boehm[1], Yong-Hee Cho[3], Alexey Belyanin[3] and Markus-Christian Amann[1]

[1] Walter Schottky Institut, Technische Universität München, Garching, Germany
[2] Dept. of Electrical and Computer Engineering, The University of Texas at Austin, Austin, Texas, USA.
[3] Dept. of Physics, Texas A&M University, College Station, Texas, USA.

email: augustinas.vizbaras@wsi.tum.de

GaInAs/AlInAs/InP quantum cascade lasers (QCLs) have established themselves as reliable, high power mid-infrared (MIR) lasers sources in the wavelength range between 3.5 µm – 12 µm. There, room-temperature (RT), continuous-wave (CW) operation with output powers up to several Watts has been reported [1]. The growth and fabrication process of GaInAs/AlnAs/InP QCLs is compatible with telecommunication diode lasers production lines which makes manufacturing cost-efficient. However, it is difficult to generate wavelengths above and below 3.5 – 12 µm in these devices. Short-wavelength lasers suffer from increased carrier scattering into the continuum and into the indirect valleys of the well material. Long-wavelength devices suffer from large free-carrier absorption and reduced population inversion due to the short upper-state lifetime. A promising alternative approach for light generation in these "difficult" wavelength regions may be the nonlinear frequency conversion. This method is particularly attractive for QCLs due to the possibility of monolithic integration of multi-quantum-well nonlinear optical media with QCLs [2].

In this work we will present nonlinear QCL sources operating in the $\lambda \approx 2.7 - 3.5$ µm range and at $\lambda \approx 70$ µm. Our device design is based on growing a passive nonlinear layer (NL) on top of the pump QCL active region. Intersubband states in the NL are designed to produce a giant optical nonlinearity for efficient laser frequency conversion. Such integration of passive NL and the laser active region has several advantages. First, the passive NL can be modified independently from the QCL active region. Second, the NL can be patterned for quasi-phase-matching (QPM) between TM_{00} modes of the pump and the nonlinear signals. Third, the carrier density in the NL structure is dependent on the local doping concentration rather than the threshold condition of the pump laser, which results in larger nonlinearity.

Our current devices based on intracavity second-harmonic generation deliver room-temperature SHG output powers above 30 µW and provide spectral coverage down to 2.7 µm. Their room-temperature threshold current density is below 3 kA/cm^2. Long-wavelength ($\lambda = 70$ µm) devices, based on difference-frequency generation (DFG), provide ~ 100 nW of DFG output power and operate up to 210 K. We will discuss future steps to increase power output in these devices and the concept of ultra-broadband QCLs with mW-level power outputs both in the 2.5 – 5 µm range (using the SHG signal) and the 5 – 10 µm range (using the fundamental signal).

TU Munich team acknowledges the financial support of the Excellence Cluster "Nanosystems Initiative Munich (NIM)", UT Austin and Texas A&M University teams acknowledge Texas Higher Education Coordinating Board "Norman Hackerman Advanced Research Program" award, and the National Science Foundation grant number ECCS-0935217.

[1] M. Razeghi, IEEE J. Select. Top. Quantum Electron. **15**, No. 13, pp. 941-950 (2009).
[2] M. M. Fejer et al., Phys. Rev. Lett., **62**, No. 9, pp. 1041-1044 (1989).

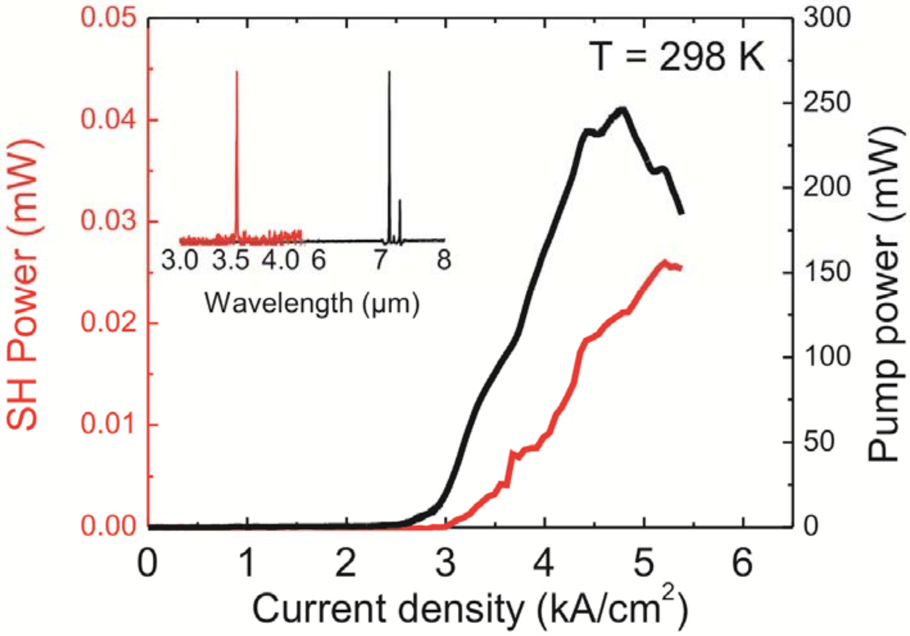

Fig. 1: Room-temperature pulsed output power vs. current density for the fundamental (black line) and the second-harmonic signal (red line). The emission spectrum of this device is presented in the inset of the graph.

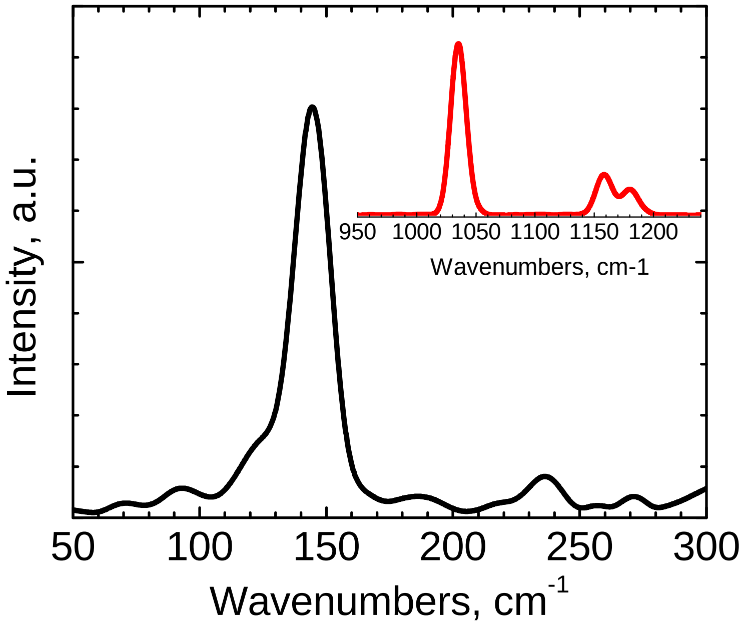

Fig. 2 THz emission spectrum of the long-wavelength device at T = 80 K. The corresponding emission spectrum of the Mid-IR pump signal is shown in the inset of the graph.