

InP-based quantum cascade lasers with transversely integrated giant nonlinearity for wavelength generation in the 2.6 μm – 70 μm range by intracavity nonlinear frequency mixing

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InP-based quantum cascade lasers (QCLs) are known to be very reliable Mid-IR sources in the wavelength range between 3.8 μm - 11 μm . However, wavelengths above and below this spectral range are difficult to generate. Short-wavelength devices suffer from carrier scattering into indirect valleys, whereas long-IR and THz devices suffer from high intrinsic loss, and reduced upper laser state lifetime. An alternative approach to generate very short and long wavelengths is to use nonlinear frequency conversion. This is particularly attractive for QCLs as intersubband transitions in quantum wells can be designed to exhibit giant nonlinear properties. Furthermore, intracavity integration of such nonlinearities with active QCLs is possible.

Here we report a novel device concept which includes a QCL with a transversely integrated nonlinear (NL) structure. For short-wavelength generation (2.5 μm - 4 μm) the concept of second-harmonic generation (SHG) was used. Here, a two-well nonlinear structure was grown on top of the injectorless mid-infrared quantum cascade laser active region, which served as a pump. Such transverse integration provides several advantages: first, it allows patterning of the NL layer into quasi-phase-matching (QPM) gratings, which compensate the inherent wavevector mismatch between the pump and SH waves in our device; second, it provides additional design flexibility, as it is possible to optimize the NL structure without modifying the pump active region. To prove the flexibility of this approach we demonstrate two frequency doubled QCLs emitting at $\sim 2.7 \mu\text{m}$ and $\sim 3.5 \mu\text{m}$ up to room-temperature (RT) operating at low current densities with record-high conversion efficiencies.

Similarly, difference-frequency generation (DFG) is exploited for devices emitting in the THz spectral range. In this work, we used a reliable, RT operation capable, dual-color mid-IR QCL active region ($\lambda \approx 8.4 \mu\text{m}$, and $\lambda \approx 9.5 \mu\text{m}$), which pumped a transversely integrated giant nonlinearity. This two-well NL structure was designed to have a resonant nonlinear response for the two pump waves, which resulted in the generation of a $\lambda \approx 72.5 \mu\text{m}$ wave. Due to high free-carrier absorption and resonant losses at THz and MIR frequencies, the NL section was implemented only close to the exit facet of the laser (last 200 μm of the total laser length). Additionally, tapering was introduced at the exit facet to improve the out-coupling of the THz wave. Our first THz devices operated up to 210 K with output powers of $\sim 100 \text{ nW}$.

We demonstrate that if the NL structure is designed to be resonant with the pump frequency, above mW level of SH output power with an internal conversion efficiency of $\sim 10 \text{ mW/W}^2$ should be viable in the entire 2 μm - 4 μm wavelength range. Similar performance and RT operation is expected for DFG devices optimized for the THz frequency range as well.

Figures

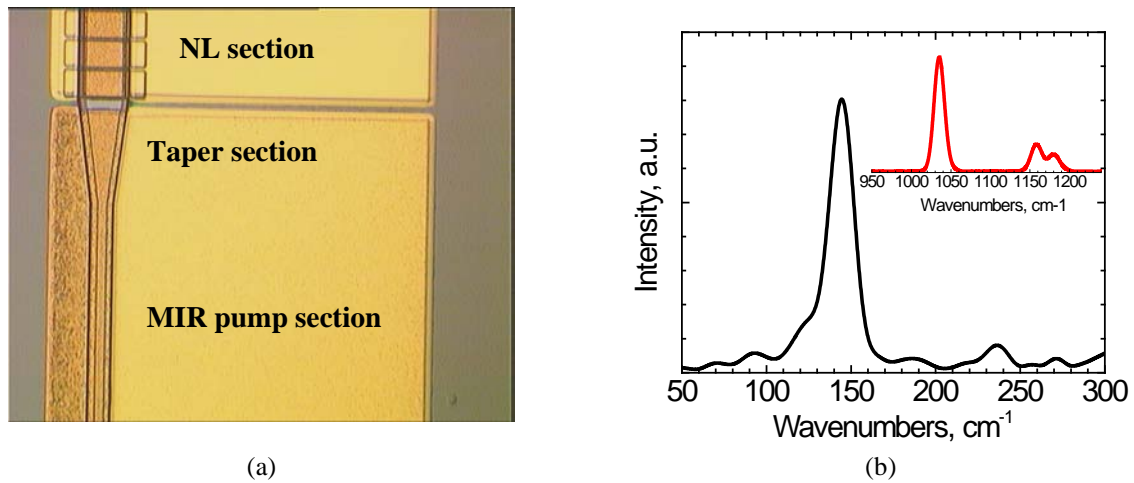


Fig. 1. (a) Optical microscope picture of our DFG-QCL device. The important device parts are indicated in the picture. (b) Normalized THz emission spectrum for one of our DFG devices at 80 K. The inset in the graphs shows the emission spectrum of our pump waves. Device was operated in pulsed mode with 2 % duty cycle.

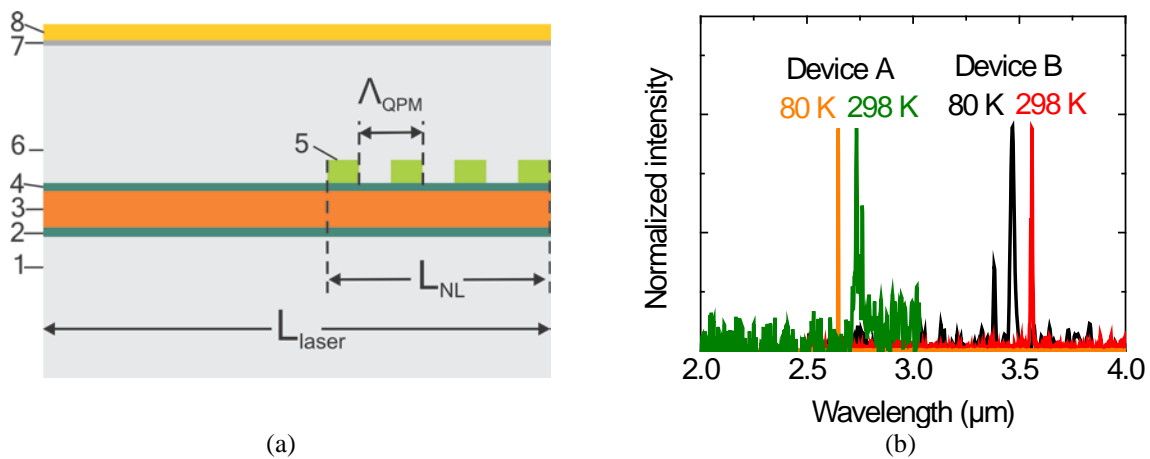


Fig. 2. (a) Schematic longitudinal section of the SH-QCL device. L_{laser} is the length of the laser, L_{NL} is the length of the NL grating. Λ_{QPM} is the period of the QPM grating. The numbers in the figure indicate the following layers: 1- low-doped InP substrate, 2- lower GaInAs cladding, 3- pump QCL active region, 4- top GaInAs cladding, 5- NL layer, 6- low doped InP waveguide, 7- GaInAs contact layer, 8- top Ti/Pt/Au contact. (b) Normalized emission spectra for two device generations at 80 K and 298 K. Devices were operated in pulsed mode with 0.75 % duty cycle