# Quantum cascade lasers with integrated nonlinearity for difference-frequency (THz) and second harmonic (near infrared) generation

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**Abstract**

Quantum cascade lasers have recently developed into efficient low-threshold devices in the mid-infrared spectral region. Due to their highly efficient gain region, particularly in case of the injectorless designs /1/, sufficient design flexibility is given to realize dual-wavelength emitters and to integrate nonlinear sections for extended functionality such as difference-frequency /2/ or second harmonic generation. In this way, a wavelength range between ~2.5µm and >60µm (THz-regime) becomes principally accessible for room-temperature InGaAs/AlInAs devices. This includes 'difficult' wavelength regimes such as the 3-4 µm range and the THz range, where the direct generation at room-temperature by semiconductor laser sources is challenging or even impossible.

Our devices have passive InGaAs/AlInAs multi-quantum-well sections with giant optical nonlinearities, associated with intersubband transitions, monolithically integrated on top of an InGaAs/AlInAs quantum cascade laser active region /3/. A consistent epitaxial technology is applied to the entire device. Since true phase-matching between $TM_{00}$ modes is impossible for second-harmonic generation, a quasi-phase-matched nonlinear structure is applied there; true phase-matching is used for difference-frequency generation. A schematic longitudinal section of the integrated device is shown in Fig. 1, where the QCL pump is either single-wavelength aimed for second-harmonic generation or dual-wavelength for difference frequency generation. First results on THz-emitters based on 8-10µm dual-wavelength injector-based quantum cascade laser pumps showed output powers of 100nW up to 210K at about 80µm wavelength (~3.8THz). The second-harmonic generation from 5.4µm single-wavelength injectorless quantum cascade laser pumps has yielded record-high conversion efficiencies to 2.7µm wavelength with >1mW output power at 80K and still ~10µW at room-temperature.

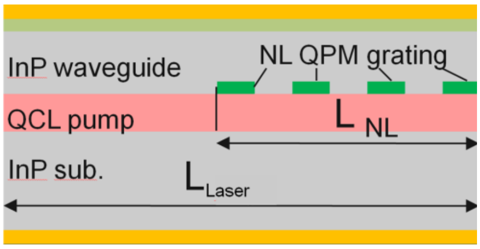


*Fig. 1 Schematic cross-section of (injector-less) quantum cascade laser integrated with a multi-section nonlinearity for difference and/or sum frequency generation using quasi-phase matching*

In summary, the integration of single- and dual-wavelength quantum cascade lasers with nonlinear optical sections based on intersubband transitions proved successful in the realization of THz sources and devices operating in 2.5-4µm spectral range. Significant improvement in conversion efficiency and output power of these first devices can be expected by further optimization, particularly with respect to the exact matching of the resonant nonlinearity to the pump wavelengths.

**References:**

/1/ S. Katz et al. *"Injectorless quantum cascade laser with two-phonon-resonance design using four alloys for emission wavelengths between 5 and 9 µm", Semicond. Sci. Technol.* ***26*** *(2011) 014018.*

/2/ R. W. Adams, et al. *"Terahertz sources based on difference-frequency generation near exit facets in dual-wavelength mid-infrared quantum cascade lasers", CLEO 2010, San Jose, USA, paper CTuMM6.*

/3/ See, e.g., C. Sirtori, et al., *"Observation of large second-order susceptibility via intersubband transitions at λ~10µm in asymmetric coupled AlInAs/GaInAs quantum wells,"* Appl. Phys. Lett. **59,** 2302 (1991).