THz Emission by Difference-Frequency Generation in Single-Active Region Quantum Cascade Lasers

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***Abstract* — We demonstrate a novel laser design for room temperature THz emission from a quantum cascade laser. The device concept is based on THz emission by difference-frequency generation in mid-infrared quantum cascade lasers with giant nonlinear properties. In contrast to previously demonstrated lasers the presented design significantly simplifies and improves the active medium of the quantum cascade laser. The demonstrated laser accommodates only a single design for the active region which is optimized for ultra-broad gain for dual-wavelength operation in the mid-infrared. Additionally, the design accommodates a giant nonlinearity which is optimized for difference-frequency generation.**

I. INTRODUCTION

An emerging technology for compact and efficient THz sources is the difference-frequency generation (DFG) in nonlinear quantum cascade lasers (QCLs) [1]. The crucial part is the utilization of an active region for the mid-infrared (MIR), which operates well at room temperature contrary to its direct THz counterpart. As QCLs emitting in the mid-infrared are well established and easily generate several watts of output power, they are perfectly qualified to serve as optical pumps for a nonlinear process such as DFG [2]. As two MIR wavelengths are required for the nonlinear conversion process and their spectral spacing corresponds to the generated THz, the necessary gain requires a much broader spectral width in the mid-infrared than a conventional MIR QCL can provide. Previously realized devices addressed this problem by implementing two separate active regions stacked on top of each other. Each active region was optimized for one single wavelength while additionally providing a giant nonlinear susceptibility $\chi^{(2)}$. As the index guided modes experience the sum gain of both active regions, dual-emission can be achieved [3, 4]. However, this approach is prone to parasitic lasing as the sum gain shifts the gain peaks away from the desired resonances and induces gain peaks at undesired wavelengths. Furthermore, the integrated nonlinearity is the sum of two different sets of intersubband transitions with none of them being resonant to the actual provided optical pumps.

We present a novel design that significantly simplifies and improves the active medium by fitting all requirements into a single active region design.

II. Active Region Design

The demonstrated novel design approach for the active region is optimized for providing an ultra-broadband MIR gain. Considering the intersubband structure of the design, this is achieved by creating a two-fold optical transition with two separate lower laser states that utilize the same upper laser level. As the structure now offers two dominant transitions, the gain experience a spectral broadening in accordance to the energy separation of the two lower laser levels. The resulting gain of the structure depends on the life times of each involved state, the dipole matrix element of the transitions and their corresponding energy separation. In the presented device, these properties are designed to be equal for the two desired wavelengths, resulting in a symmetric and flat MIR gain profile. The resulting intersubband gain provided by the multi quantum well structure is hence broad enough to support two distinct wavelengths in the mid-infrared. As this broadening is realized by a manifold of possible intersubband transitions, the structure also provides a second order nonlinearity. By utilizing only one active region design, both pumps are perfectly resonant to this monolithically integrated nonlinearity which leads to an increased nonlinear susceptibility of $|\chi^{(2)}| = 29\ \mathrm{nmV^{-1}}$.

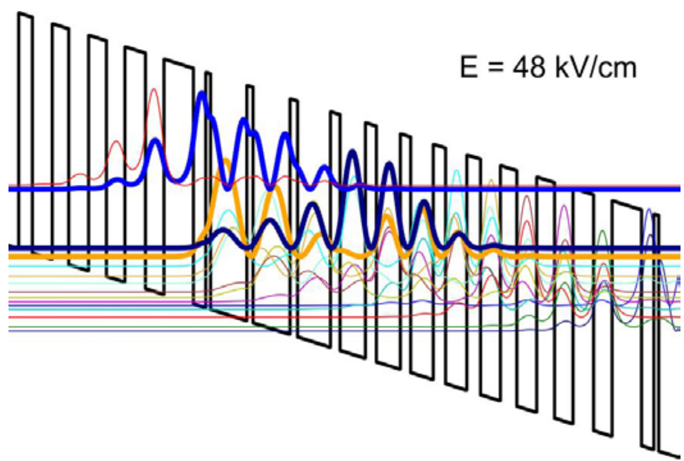

Fig. 1. Subsequent periods of the nonlinear active region design using **AlInAs**/GaInAs lattice-matched on InP. The thicknesses in nm are **4.3**/1.8/**0.7**/5.3/**0.9**/5.4/**1.1**/4.8/**1.4**/3.7/**1.6**/3.5/**1.5**/3.3/**1.8**/3.1/**2**/2.9/**2.4**/2.9/**2.6**/2.7/**3**/2.7 where underlined thicknesses represent doped layers ($2 \times 10^{17}\ \mathrm{cm^{-3}}$). The three bold wave functions indicate the main optical transitions which are used in this design, with one upper level and two lower levels. Both optical transitions contribute equally to the gain of the structure, leading to a broad and symmetric gain profile compared to conventional active regions. Simultaneously they provide an optical nonlinear susceptibility $\chi^{(2)}$, which peaks for the THz frequency equivalent to the energy separation of the two lower laser levels.

III. Waveguide Design

For efficient MIR to THz conversion, spectrally pure MIR modes are desired. As the gain profile is spectrally broad, a simple Fabry-Pérot resonator does not yield the necessary spectral purity. Selective optical feedback is achieved by a distributed feedback (DFB) grating. The grating is realized as an index-coupled grating and hence fabricated right on top of the active region for optimum coupling. As this DFB grating needs to provide feedback at two distinct wavelengths, a design based on the modulation principle is chosen. This grating design type has a two spatially convoluted grating periods, resulting in a double resonance in the mid-infrared for dual-emission. The separation of both modes is designed to result in a DFG signal at 3.8 THz.

IV. Fabrication

The first epitaxial step includes the lower wave cladding, active region and the DFB layer grown by molecular beam epitaxy (MBE). For the active region, the design for one period is grown 66 times in order to achieve a total thickness of 4.4 µm. The DFB grating is structured by electron beam lithography, etched by reactive ion-etching and overgrown with the upper wave cladding and contact layer by metal-organic vapour deposition. Afterwards the laser is processed as a conventional edge emitter and anti-reflection coated on both facet ends.

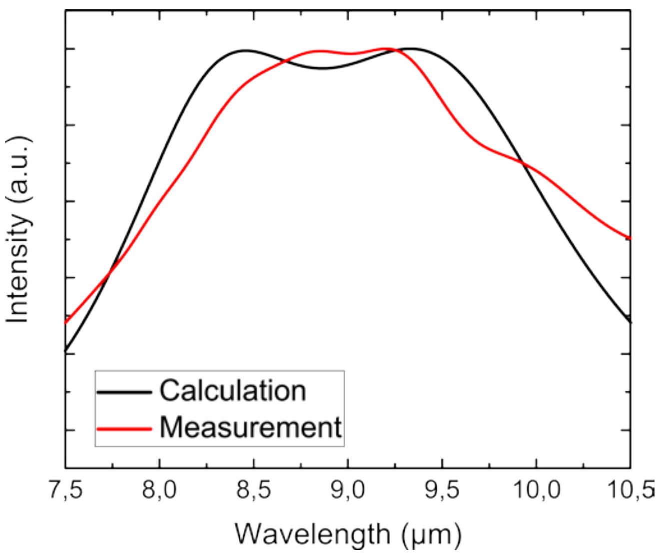

Fig. 2. The expected gain provided by the structure is calculated and plotted in black. From the calculation it becomes clearly visible that the active region is designed to provide a broad and symmetric gain shape in order to support two separate infrared laser modes. In order to compare the device performance to the calculation, a spectral measurement of the electroluminescence (red) is recorded at the designed voltage drop. A spectral broadening of the gain profile in comparison to conventional active regions becomes clearly visible, which indicates multiple possible optical transitions in the demonstrated design.

V. Results

Electrolumiscence (EL) is measured to characterize the gain profile of the structure. In fig. 2 the calculated gain and the recorded EL spectra is plotted for comparison. Overall, the measurement shows good agreement with the calculation. The spectral broadness of the EL indicates a much broader gain profile than previously demonstrated stacked active region designs [3, 4]. Laser samples are accordingly processed as DFB edge emitters and cleaved into bars of 2 mm. The front facet is polished to increase THz extraction. Spectral measurements in the mid-infrared yield two distinct mid-infrared peaks, corresponding to the dual-resonance of the modulated DFB. The optical intensity of both modes are in the same range, which indicates a broad and even gain profile of the single active region design. THz measurements show emission at 3.77 THz as expected from the MIR spectrum. All measurements are recorded at room temperature.

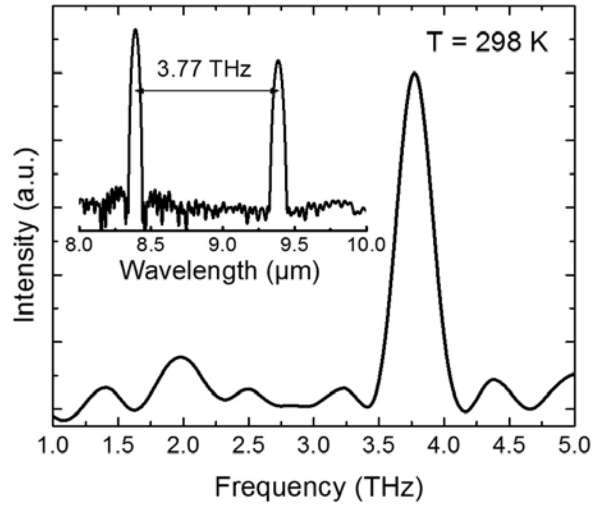

Fig. 3. The inset shows the mid-infrared emission characteristics of the demonstrated device. The mid-infrared spectrum shows clear dual-emission at the designed wavelengths for the integrated buried DFB structure. THz emission is recorded at 3.77 THz, which fits perfectly to the corresponding optical pumps in the mid-infrared. All measurements are recorded at room temperature with the laser operating in pulsed mode.

VI. Summary

In conclusion, we presented a nonlinear quantum cascade laser emitting in the THz range while operating at room temperature. The active region consists of a single design, optimized for both ultra-broad gain and a giant nonlinearity. The provided gain of this design is broad enough to support two distinct MIR modes selected by the buried DFB grating, while the integrated nonlinearity is optimized for its corresponding THz emission by DFG.

Acknowledgement

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