Nonlinear light generation in GaAs quantum-cascade lasers

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***Abstract*— We report second-harmonic and sum-frequency generation in GaAs based quantum cascade lasers. Different waveguide designs and active regions were investigated as well as a doping dependence study of the second-order susceptibility in one of the investigated structures is shown. We present farfield measurements which give information about the modal behavior depending on the waveguide design and dimensions. We also demonstrate that grating-coupled surface emission is a highly efficient way to couple out the second-harmonic radiation.**

***Index Terms*—quantum cascade lasers, second-harmonic generation, distributed-feedback laser, surface emission**

I. INTRODUCTION

THE principle of nonlinear light generation in QCLs was firstly demonstrated in 2003[1]. Since then a lot of progress in this field has been made, such as the improvement of SH generation[2] and the demonstration of third-harmonic generation[3]. A crucial step was the achievement of phase-matching[4], which was demonstrated by means of modal phase-matching in tailored QCL waveguides. Another approach for higher conversion efficiencies is quasi phase-matching by periodically modulating the pump current along the QCL ridge waveguide[5]. Besides up-conversion, other intracavity nonlinear effects are currently being investigated, such as Raman lasing[6] and anti-stokes[7] emission from QCLs. All of the mentioned nonlinear effects are due to higher-order susceptibilities of intersubband transitions. Although InP and GaAs, both of which are commonly used as host materials for QCLs, have nonzero second-order susceptibilities, there is no resulting second-order polarization in the material for QCLs. Selection rules for intersubband transitions allow gain only for TM polarized light, which in turn due to crystal symmetry cannot excite nonlinear polarization in the host material. However it was shown that QCLs grown on <111> substrates, show sum-frequency generation due to bulk nonlinearity[8]. Another very interesting topic is intracavity difference-frequency generation in QCLs. It could eventually be used to generate coherent terahertz radiation in a semiconductor laser at room temperature. THz sideband generation from a THz QCL and a near-infrared diode laser has already been shown[9].

In our work we studied intersubband nonlinearities of GaAs based QCLs. The bandstructure of typical laser designs often intrinsically include electronic energy levels that resonantly enhance second-harmonic generation. These effects have been studied for different active region designs and the resulting nonlinear conversion efficiencies are discussed. We show that the second-harmonic generation efficiency depends on the doping level in the active region and propose that the optimization of the doping might also lead to improved SH generation.

As with most nonlinear processes phase-matching is the most crucial point when it comes to external nonlinear conversion efficiencies. We present detailed farfield characterization of the nonlinear emission from the waveguides. By studying various waveguide designs we optimized our waveguides for modal phase matching. Also the influence of DFB gratings of different orders on the nonlinear performance is presented.

II. SAMPLES & DISCUSSION

We compared a three-well design with AlAs barriers (structure A)[10], a three-well design with $Al_{0.45}Ga_{0.55}As$ barriers (structure T) and a bound-to-continuum design with $Al_{0.45}Ga_{0.55}As$ barriers (structure B) with respect to there second-harmonic generation performance. In table 1 the transition energies and dipole matrix elements for the corresponding electronic transitions are given. For structure T three nominally identical wafers were grown, with the only difference being the average doping in the active region: structures T1, T2 and T3 with doping densities of 8.8e16 cm^{-3}, 4.4e16 cm^{-3} and 2.2e16 cm^{-3}, respectively. The conversion efficiency changed drastically with the doping level, giving insight into the optimum carrier concentration needed[11]. These structures were fabricated with both double-plasmon enhanced waveguides and low-dispersion double AlGaAs

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waveguides in order to minimize the phase-mismatch between the fundamental and second-harmonic fields. The best second-harmonic performance was observed for structure B with the low-dispersion AlGaAs waveguide. Using this material surface-emitting distributed-feedback lasers (DFB) were fabricated, where the grating was designed such as to emit only second-harmonic radiation from the surface (Fig. 1)[12]. Due to the resonant nature of the grating the laser and thus the frequency-doubled light were single-mode.

	A	T	B
E_{32} / [meV]	117	143	124
z_{32} / [nm]	1.53	2.09	2.07
$E_{43(5c3)}$ / [meV]	128	148	128
$z_{43(5c3)}$ / [nm]	0.11	0.22	0.6

Tab. 1. Energies and optical matrix elements for relevant transitions in structures A, T and B. States 3 and 2 are the upper and lower laser states, state 4 is lying energetically above level 3 and resonantly enhancing second-harmonci generation. The values depend on the applied electric field across the structure.

With the low-dispersion AlGaAs waveguides, depending on the ridge width we were able to increase the conversion efficiency from approximately 15 to 100 μW/W^2 and achieve nonlinear peak powers exceeding 100 μW. This improved performance is due to a higher confinement and lower losses for the SH light. According to our calculations the overall refractive index difference between the fundamental and SH is also reduced, and it might be possible to achieve modal phase matching in such a waveguide.

Farfield patterns of the facet and surface emissions were recorded and analysed to give insight into the phase-mismatch, in particular angularly and spectrally resolved measurements of the surface emission patterns.

III. CONCLUSION

Second-harmonic and sum-frequency generation in GaAs QCLs due to intersubband nonlinearities are well controlled and were used to investigate waveguiding/phase-matching issues as well as the effects and benefits of grating coupling. The influence of different active region designs and doping control were shown, our current work is aiming at exploring further nonlinear effects and their combination with distributed feedback gratings for coupling out the generated radiation.

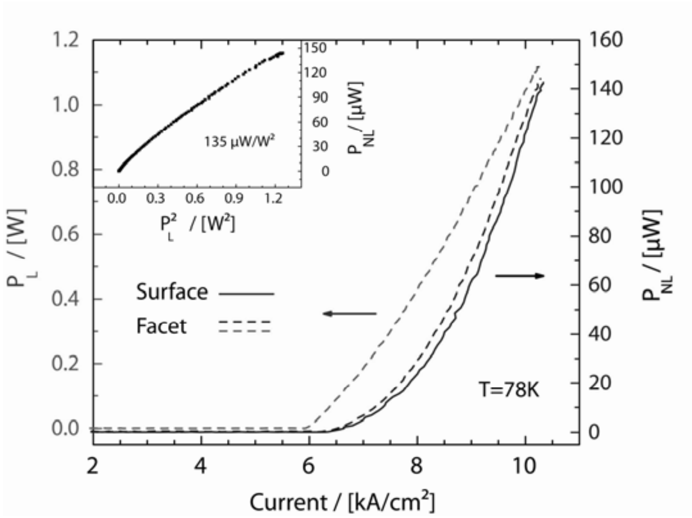

Fig. 1 Light output vs. current characteristics at a heat sink temperature of 78 K for a SH DFB laser (width 40 μm, length 1.95 mm) fabricated from material B with AlGaAs waveguide. The dashed lines show the single facet emission and the solid line the surface emission. Inset: The linear to nonlinear external conversion efficiency is plotted. A linear fit to the data yields a slope of 135 μW/W^2.

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