Vertical Second-Harmonic Emission from Quantum Cascade Lasers

M. Austerer, S. Schartner, M. Nobile, W. Schrenk, A. M. Andrews, T. Roch, and G. Strasser

Zentrum für Mikro- und Nanostrukturen, TU Wien,
Floragasse 7, A-1040 Vienna, Austria

We report surface emission of second-harmonic radiation generated in the cavity of GaAs/AlGaAs quantum cascade lasers. Intersubband nonlinearities in the active region of the quantum-cascade laser lead to second-harmonic generation. A distributed-feedback grating etched into to the top of the semiconductor surface provides for both single-mode fundamental laser operation and for surface-emission of the frequency-doubled light. The optical peak power from the surface is approx. 130 µW of SH light at 5.35 µm wavelength for ~1 Watt of fundamental optical power (10.7 µm) at liquid-nitrogen temperatures.

Introduction

Nonlinear light generation in quantum cascade lasers (QCLs) has first been demonstrated for the case of sum-frequency generation in the InGaAs/InAlAs material system [1], [2]. It has the potential to extend the emission wavelength region both to the high energy side by second-harmonic (SH) generation, and also to the low energy side by means of difference frequency generation. The latter process has not been demonstrated yet in QC lasers, whereas SH generation has already been combined with phase-matching schemes in order to increase the nonlinear conversion efficiency [3], [4]. In our work we used distributed-feedback (DFB) gratings in order to couple out the SH radiation via the surface of ridge lasers. The fundamental radiation is not coupled out from the surface, yielding vertical single-mode emission of SH light only.

Design and Fabrication

The laser material was grown by molecular beam epitaxy on n-doped GaAs substrates. It consists of a bound-to-continuum GaAs/AlGaAs active region and a double AlGaAs waveguide. The layer sequence of the heterostructure is as follows: 0.3 µm GaAs ($n_{Si} = 4x10^{18}cm^{-3}$), 0.7 µm $Al_{0.9}Ga_{0.1}As$ ($n_{Si} = 2.4x10^{17}cm^{-3}$), 2 µm GaAs ($n_{Si} = 4x10^{16}cm^{-3}$), four stacks of 15 cascades of bound-to-continuum active cells, each stack separated from the next by 150 nm GaAs spacer layers, 2.2 µm GaAs ($n_{Si} = 4x10^{16}cm^{-3}$), 0.7 µm $Al_{0.9}Ga_{0.1}As$ ($n_{Si} = 2.4x10^{17}cm^{-3}$), 1 µm GaAs ($n_{Si} = 4x10^{18}cm^{-3}$) and n-type GaAs substrate. The active region is described in detail in Ref. [5].

The DFB grating period, etch depth and duty cycle were optimized for efficient surface emission of the SH light. Our calculations yielded a grating period of 1.72 µm, an etch depth of 800 nm with a grating mark-space ratio of 0.6 and 200 nm of gold on the grating peaks only. The grating trenches were left void of metal in order to let the light couple out. The rectangular grating was transferred to the semiconductor by optical contact lithography and dry-etching. Ridge waveguides, 30 to 50 µm wide, were defined by dry-etched trenches. 300 nm of SiN_x were deposited for electrical insulation of the extended Ti/Au contact pads. The lasers were cut to approx. 2 mm long bars and indium soldered substrate down onto copper submounts. The measurements were performed in a temperature controlled liquid-nitrogen cooled cryostat fitted with a ZnSe window. The fundamental and SH light was collected by uncoated ZnSe lenses and gold-coated off-axis parabolas and fed into a Bruker Fourier-Transform Infrared Spectrometer (FTIR). For the fundamental light a LN_2 cooled HgCdTe detector was used. The SH radiation was detected with a LN_2 cooled InSb detector fitted with an additional sapphire window to block all fundamental laser light.

Experimental

Sample Preparation

The DFB grating has a twofold function: It provides single-mode operation for the principal laser action, and couples out the second-harmonic radiation that is generated in the laser cavity by intersubband nonlinearities. The optical power at SH frequency is a function of the material second-order susceptibility χ_2 and the mismatch of the propagation constants between the fundamental and SH cavity modes. Fabry-Perot devices fabricated from the same semiconductor material show external linear-to-nonlinear conversion efficiencies $\eta_{nonlinear}$ between 10 and 130 µW/W^2 depending on the ridge width of the respective devices. We attribute that to varying phase-mismatches.

The surface-emitting DFB lasers show a $\eta_{nonlinear}$ of ~130 µW/W^2 for both facet and surface emissions. For a more detailed description of these devices refer to Ref. [6]. In Fig. 1 the light output vs. current characteristics of a typical DFB laser is shown. The investigated devices showed single mode operation on both the fundamental and SH wavelengths, as can be seen in Fig. 2. Due to the resonant nature of the DFB grating, the SH light exits the surface at nearly 90° from the ridge surface. The measurement of the exact emission angle could yield the exact difference in refractive indices for the fundamental and SH light. Furthermore the surface-emitting device allows to collect the SH radiation without the necessity of blocking filters for the fundamental frequency, as it is necessary when facet output is used.

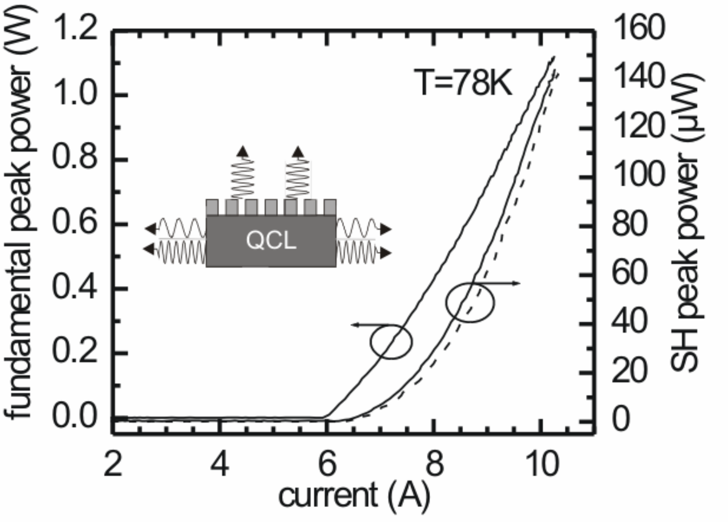

Fig. 1: Light output plotted against drive current for a 40 µm wide, 1.95 mm long device. The solid lines refer to single facet emission, the dashed line refers to vertical surface emission. Inset: A schematic depiction of the QC DFB laser ridge with fundamental (low-frequency arrows) and SH (high-frequency arrows) emissions.

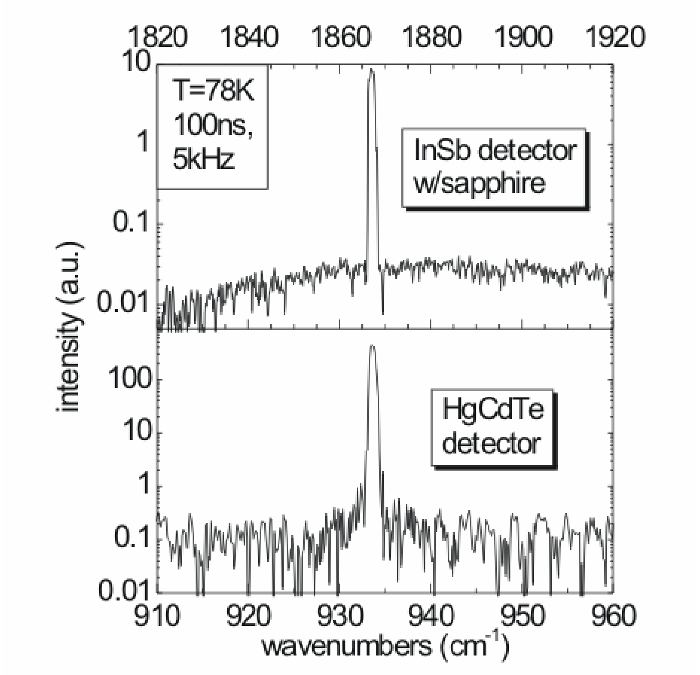

Fig. 2: Emission spectra from a 50 µm wide and 1.95 mm long device, collected from the facets. The laser was operated at 78 K under a pulsed bias of 8 A. The bottom trace shows the fundamental single-mode wavelength, whereas the top trace shows the signal at the second-harmonic frequency. The spectra were recorded with an FTIR in rapid-scan mode.

Conclusion

In conclusion we have shown that SH light generated in the cavity of a QC laser can be coupled out via the surface by means of a DFB grating. Surface gratings might also be useful for difference-frequency generation applications, or could be used for quasi-phase matching schemes, where destructive interference is suppressed by an appropriate grating.

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