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Quantum Cascade Laser with Uni-Lateral Grating

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***Abstract*—We report room temperature, distributed feedback quantum cascade lasers operating at wavelength of 3.58 µm. Single mode emission with side-mode suppression ratio (SMSR) of 30 dB is achieved by manufacturing single-sided, third order, lateral gratings. The devices exhibit watt level peak powers with the threshold current density of ~ 4.3 kA/cm^2 at room temperature and remain in single mode operation over the temperature range of 280 K – 420 K.**

***Index Terms*—Distributed feedback, lateral grating, single mode, uni-lateral, quantum cascade laser.**

I. Introduction

SINGLE mode operation and high output powers are two main requirements for lasers used in spectroscopic applications. A number of important hydrocarbons absorb light in the mid-infrared region, especially in the λ = 3 – 3.5 µm range creating the need for suitable single mode light sources. The quantum cascade lasers (QCL) considered to be very promising candidates of reaching these wavelengths, compared with interband GaSb based laser diodes [1] or interband cascade lasers [2], due to potentially higher output powers, wider operating temperature range and broad wavelength selection [3]. However, the complexity of the single mode design quite often results in lower device yield. Simplification of processing steps is one of the most effective ways to bring manufacturing costs down and increase the number of working lasers.

There are a number of methods for achieving single mode operation in QCLs, including the use of external cavity, distributed Bragg reflector mirror or distributed feedback (DFB) grating. Since the first demonstration of DFB QCL in 1997 [4] with metalized surface grating, various types of DFB gratings have been implemented since.

The emission wavelength for a DFB laser can be chosen by tuning grating pitch according to $\lambda_B = 2\Lambda n_{eff}/m$, where λ_B, Λ and n_{eff} are the Bragg wavelength, grating pitch and effective refractive index of the laser core respectively and m is the order of the grating. To achieve lasing in the short wavelength mid-infrared region (3 µm < λ < 3.8 µm) the typical size of the features of a conventional first order grating (m = 1) have to be of the order of 250 – 300 nm. Features of this size are too small to be defined using ordinary photolithographic techniques, thus it has to be done with electron beam lithography [5]. By contrast, in a third order grating [6] the size of these features is increased to 750 – 900 nm allowing them to be defined using photolithography. However, the downside of using higher order grating is the reduction of the coupling coefficient κ that defines how strongly the optical mode is coupled to the grating [7].

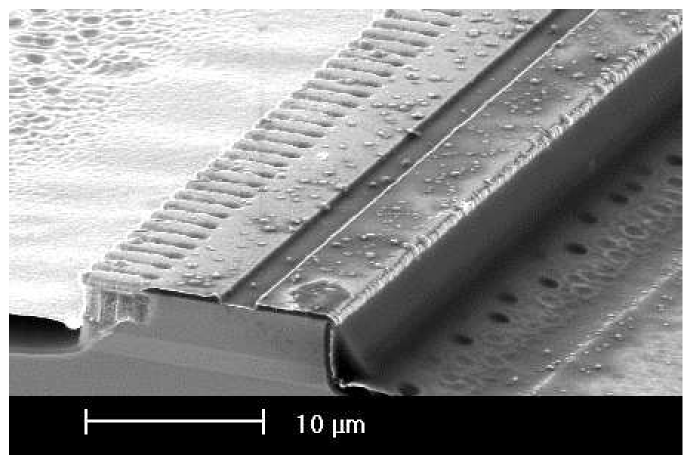

Fig 1. Scanning Electron Microscopy image of a processed quantum cascade laser ridge with single-sided lateral grating (10 µm wide plain ridge with 3 µm wide grating on one side) before deposition of electroplated gold. (The spots on the surface of the laser ridge and around are the results of the residues from SiO_2 hard mask and photoresist.)

A lateral grating has several advantages over other types of gratings. For example, in contrast with a buried grating, a lateral grating involves fewer processing stages and does not require an additional overgrowth process that is both time consuming and may introduce potential defects. Surface gratings, on the other hand, do not require an overgrowth step, but it is more difficult to control coupling due to weak mode penetration into the top cladding layer for short wavelength QCLs. The fabrication of a uni-lateral grating on only one side of the ridge, reduces the possibility of making an error in fabrication even further. Despite the fact that single-sided grating has reduced coupling coefficient compared to the double-sided structure, the coupling can be increased by adjusting the aspect ratio between grating's depth and width of the ridge. Reduced κ also means reduced sensitivity to the

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device length, allowing more flexibility during cleavage. In this paper we present DFB laser with unconventional third order, uni-lateral grating operating at the wavelength of 3.6 μm.

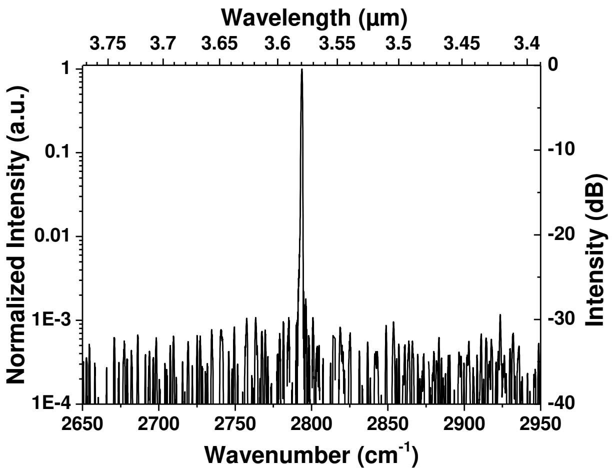

Fig. 2. Emission spectrum of 3 mm long and 10 + 2 μm wide laser ridge at 20% above its threshold current at room temperature (293 K). SMSR of ~ 30 dB is observed.

II. Device Characteristics and Modeling

The single mode lasers, designed to have lasing gain centered at 3.5 – 3.7 μm at room temperature, were manufactured from a QCL wafer with a strain compensated $In_{0.7}Ga_{0.3}As/AlAs(Sb)$ laser core design similar to that described in Ref. [8]. $In_{0.53}Ga_{0.47}As$ spacer layers of 200 nm were grown around the ~ 1.32 μm thick laser core by molecular beam epitaxy on a low doped ($3 – 5 \times 10^{17}$ cm^{-3}) n-type InP substrate. Details of the growth and upper cladding layers can be found in Ref. [9]. 800 nm of deposited SiO_2 acted as a hard mask for photolithographic definition of a one-sided grating with pre-calculated grating pitch. The structure was dry etched using $SiCl_4/Ar$ gases. 400 nm of SiO_2 was deposited using plasma-enhanced chemical vapor deposition and covered with Ti/Au (20/200 nm) and 3 μm thick electroplated gold for more efficient heat extraction.

By modelling the waveguide using commercially available software [10], the optimum grating pitch (Λ = 1.68 μm) and laser ridge dimensions were obtained, giving the Bragg wavelength and effective refractive index of λ_B = 3.57 μm and n_{eff} = 3.2 respectively. Due to possible mismatch between the actual and theoretical effective refractive index used in the computational model, lasers were processed into 10 and 5 μm wide ridges with three different grating depths ranging from 1 to 5 μm and cleaved into 2, 3 and 4 mm long chips. Such variation in the ridge size also helps to compensate for unpredictable fluctuations in coupling coefficient and effective refractive index due to under-etched grating. These imperfections can be seen in Fig. 1, where 10 μm wide plain ridge with 3 μm wide uni-lateral grating on the side is shown.

The lasers were mounted epilayer-up onto a gold plated submount with both facets left uncoated and placed inside the nitrogen cryostat. The devices were driven in pulsed mode with a pulse length of 25 – 50 ns and repetition rate of 5 kHz. The spectra were taken using a FTIR spectrometer with 0.2 – 1 cm^{-1} scanning resolution. The optical output power was measured using MCT detector calibrated against thermopile detector.

The experimental results showed that the shortest (2 mm) and longest (4 mm) devices have very low single mode yield regardless of the width of the ridge and grating, while 3 mm long lasers demonstrate much higher yield, especially for the 10 μm wide ridges. In this paper, we present laser characteristics for 10 + 2 μm wide (10 μm wide plain ridge + 2 μm uni-lateral grating on the side) and 3 mm long devices.

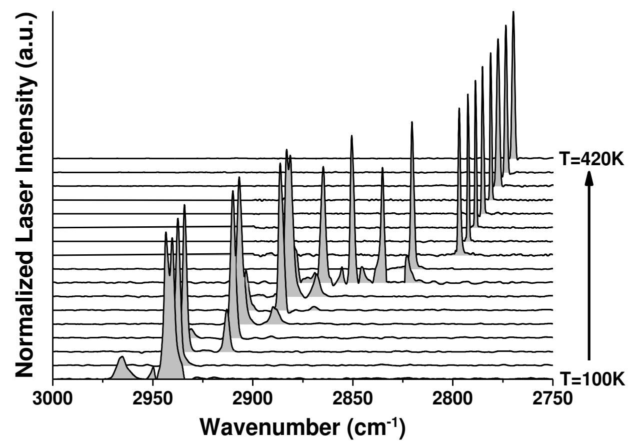

Fig. 3. Spectrum shift with the temperature from 100 K to 420 K with increment step between neighbouring spectra of 20 K. Single mode emission is observed at temperatures above 280 K. The spectra are vertically shifted for clarity.

III. Results

As shown in Fig. 2, the typical 10 + 2 μm wide device operates in single mode regime at room temperature with the side mode suppression ratio (SMSR) of ~ 30 dB. The laser wavelength of λ = 3.58 μm is in a very good agreement with the one predicted by computational model. The effective refractive index of the laser core derived from the observed emission wavelength appears to be almost identical to that used in model.

The Full Width at Half Maximum (FWHM) of the single mode emission line for the QCL driven at 50 ns current pulse was found to be 0.8 cm^{-1}. The FWHM still remained high at 0.4 cm^{-1} even after the current pulse width was reduced to 25 ns. The origin of this line broadening could lie in the fast temperature tuning rate as the device gets heated during the pulse. Emission spectra for different temperatures showing multi- and single-mode lasing are presented in Fig. 3. At temperature range from 100 K to 270 K only multi-mode operation was observed. The average emission line shift rate for Fabry-Perot type lasing was found to be $\Delta\nu/\Delta T$ ~ -1.3 cm^{-1}/K. At temperatures above 280 K the uni-lateral grating overlaps with laser gain, slowing down this shift rate to $\Delta\nu/\Delta T$ ~ -0.2 cm^{-1}/K. The device remained in single mode up to 420 K, with the wavelength increasing from λ = 3.576 to 3.61 μm as the temperature increased from 280 K to 420 K. This tuning rate is 6 times lower than that for Fabry-Perot type multi-mode operation but much higher than typical

(~ -0.08 cm^{-1}/K) value obtained for single mode quantum cascade lasers at longer wavelengths [11]. This faster wavelength shift makes these short wavelength QCLs very attractive for spectroscopic applications, since it spans over wider spectrum range.

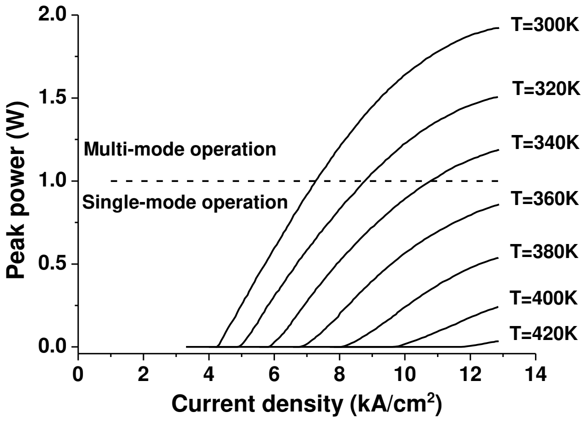

Fig.4. Light-current characteristics for the output powers measured from single facet of 10 + 2 μm wide laser ridge at different operating temperatures.

Typical threshold current density increases from 4.3 kA/cm^2 at room temperature to 11 kA/cm^2 at 420 K. At temperatures higher than ~ 350 K the laser emits in single mode regime over the whole measured current range. However, at the temperatures lower than 350 K single mode emission is only observed up to 7.3 kA/cm^2 at room temperature and up to ~ 11 kA/cm^2 at 350 K. Single mode emission exhibits maximum peak power of 1.0 W over all temperature range switching to multi-mode regime at higher powers, as shown in Fig. 4.

The presented lasers with uni-lateral grating show very resembling characteristics (threshold current and optical power) to other QCLs operating at the similar wavelengths [5,12] but manufactured with more challenging first order double sided or surface gratings. The simpler processing of the DFB lasers with single-sided lateral grating makes them more promising candidates for single mode short wavelength emitters.

IV. Conclusion

In conclusion, single mode λ ~ 3.58 μm $In_{0.7}Ga_{0.3}As/AlAs(Sb)$ QC lasers with 3^{rd} order, single-sided lateral grating have been demonstrated. SMSR of ~ 30 dB and peak power of up to 1.0 W were observed at room temperature. Single mode operation was obtained in the 280 K – 420 K temperature range. The demonstration of single sided grating opens the opportunity for further work regarding finer wavelength control in DFB lasers.

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