High power quantum cascade lasers

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Abstract. We report the most recent state-of-art quantum cascade laser results at wavelengths around 4.8 and 10 μm. At 4.8 μm, a room temperature wall plug efficiency (WPE) of 22 and 15.5% are obtained in pulsed mode and continuous wave (cw) mode, respectively. Room temperature cw output power reaches 3.4 W. The same laser design is able to reach a WPE of 36% at 120 K in pulsed mode. At 10 μm, room temperature average power of 2.2 W and cw power of 0.62 W are obtained. We also explore lasers utilizing the photonic crystal distributed feedback mechanism, and we demonstrate up to 12 W peak power operation at three different wavelengths around 4.7 μm with a waveguide width of 100 μm and diffraction limited beam quality.

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1. Introduction

Since the first demonstration of room temperature continuous-wave (cw) operation for mid-infrared quantum cascade lasers (QCLs) [1], the output power level has increased by orders of magnitude [2]–[5]. Meanwhile, QCL-based applications, such as photoacoustic spectroscopy [6], remote sensing [7], infrared countermeasures and free space communication [8], are experiencing rapid development, thanks to the availability of room temperature high power QCLs. As a measure of device quality, the wall plug efficiency (WPE) has been increased from merely a few per cent to tens of per cent through systematic exploration of structure design, material growth and device fabrication [9]. Here we report the most recent state-of-art QCL results at wavelengths around 4.8 and 10 $\mu$m, together with the result of photonic crystal distributed feedback (PCDFB) QCLs, aimed at scaling the laser output power and maintain good beam quality.

2. QCLs at $\lambda \sim 4.8 \mu$m

Recently, we demonstrated room temperature cw operation of a 4.6 $\mu$m QCL with a WPE of 12.5% and an output power of 2.5 W [5]. The form of this device was a 30-emitting stage core with a 10.6 $\mu$m wide ridge waveguide. Careful optimization of strain-balanced superlattice growth, combined with advanced thermal design, fabrication and packaging, led to this result. After some analysis, however, it was determined that significantly better performance could be obtained with some modifications.

For pulsed mode operation, the number of emitting stages in a QCL, $N$, is a very important design parameter. In general, the optical properties, such as confinement factor, $\Gamma$, and free carrier waveguide loss will decrease as $N$ is increased. This eventually leads to a lower threshold current density and higher slope efficiency, as long as spatial hole burning effects are minimal. However, since the operating voltage also scales with $N$, the WPE increases only slowly. Still, in order to achieve the highest pulsed WPE, one would grow the QCL core with the largest $N$ possible. In practice, however, a thicker QCL core severely degrades the thermal conductance of the device, which significantly impacts cw operation. Thus, a balance needs to be reached in order to have the highest WPE in cw operation, as demonstrated in [4], where $N$ is increased from 30 to 40. However, there were also design changes involved which may obscure the effect of changing the number of emitting stages.

A route to improving thermal conductance is to make use of a narrower QCL waveguide and buried ridge geometry. With this geometry in mind, it was hypothesized that a 40-emitting stage laser could, in fact, significantly improve both the pulsed and cw output power and efficiency, utilizing the same general core design.

Our QCL structure was grown in a gas-source molecular beam epitaxy (GSMBE) reactor. The core structure for each QCL stage was intended to be the same as that in [5]. Instead of a 30-stage QCL structure, we increased the number of QCL stages to 40. The core doping and the epitaxial waveguide were kept unchanged.

The buried ridge processing started with the deposition of a SiO$_2$ layer using plasma enhanced chemical vapor deposition (PECVD). The SiO$_2$ was then patterned for the desired ridge width using photolithography and etching. The remaining SiO$_2$ served as the mask for the etching of the semiconductor ridge waveguide and selective area InP regrowth around the ridge.

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After regrowth, the previously patterned SiO$_2$ was removed and a new layer of SiO$_2$ was deposited with PECVD for electrical insulation. A window was opened on top of the laser core using photolithography and plasma etching (ECR-RIE). The top contact (Ti/Au) was deposited with electron beam evaporation, with an additional 5 $\mu$m of Au electroplated on top of the QCL wafer for better heat spreading.

The bottom contact was deposited after lapping and polishing of the substrate. The substrate thickness was reduced down to about 100 $\mu$m. The bottom contact metallurgy was Ge/Au/Ni/Au. It has been experimentally demonstrated that although Ti/Au is acceptable for contact on highly doped InP, it is not an appropriate choice for the contact on low doped InP. Since we grow our QCL structure on low doped InP substrate, the bottom contact needs to be different from the top contact [9].

The processed wafer was cleaved using a semi-automatic cleaving system. Then, the laser dies were bonded either epilayer-up directly to copper heatsinks, or epilayer-down on diamond submounts, which were then soldered to copper heatsinks. Using the combination of soft indium solder and diamond submount results in packaging with the best possible heat dissipation capabilities, however, for better long term reliability, a more reliable solution widely accepted in industry consists of soldering the laser chips using the hard solder AuSn and AlN submounts.

Shown in figure 1 is an SEM image for the front facet of a device epi-layer down bonded to a diamond submount. The 8.6 $\mu$m wide QCL core is clearly distinguishable from the surrounding materials, which are exclusively InP.

Testing was done on a thermoelectric cooler (TEC) stage at room temperature and above. For low temperature testing, the lasers were mounted inside a liquid nitrogen cooled cryostat. For CW measurement, the optical power was measured with a calibrated thermopile detector placed directly in front of the laser facet. The peak power in pulsed mode operation was measured using the same calibrated thermopile detector with a 500 ns pulse width at 5% duty cycle. When using the cryostat, the thermopile was placed just outside the cryostat window, and calibrated based on room temperature pulsed testing on the TEC stage.

**Figure 1.** Scanning electron microscope image for the laser facet of an epi-layer down bonded QCL.
Figure 2. Power–current–voltage (a) and WPE-current (b) behavior of an uncoated QCL operating in pulsed mode at temperatures between 80 and 298 K. The cavity length and ridge width were 5 mm and 8.6 µm, respectively. The device was epi-side up bonded to a copper heatsink. The pulsing duty cycle was 5% with a pulse width of 500 ns. The total output power accounts for the power from both facets.

The temperature dependent behaviors tested in the pulsed mode operation are presented in figure 2, in which an uncoated device with a cavity length of 5 mm was epi-layer up bonded to a copper heatsink and loaded inside a liquid nitrogen cooled cryostat.

The temperature dependent power performances can be read from the power–current (P–I) curves of figure 2(a). First of all, the rollover current, i.e., the current at which the output power saturates, increases monotonically as a function of temperature, which can be
understood by the decrease of the upper laser level lifetime and the increase of the ionization of the dopants as the temperature increases. The second noticeable feature of the temperature dependent $P−I$ curves is that the slope efficiency at 80 K (6.6 W A$^{-1}$) is about 5% lower than that at 120 K (6.93 W A$^{-1}$), which is contradicting the expectation of more efficient operation at a lower temperature, since the upper laser lifetime decreases with temperature. We attribute this behavior to a reduced injection efficiency at sufficiently low temperatures. The core doping and the subband alignment of this particular QCL structure are designed for the best operation at room temperature. If low temperature operation is desired, the 80 K performance can be improved dramatically.

Above 120 K, the slope efficiency decreases monotonically to 4.85 W A$^{-1}$ at 298 K, which is about 0.12 W A$^{-1}$ per QCL stage. The increase of the threshold current as a function of temperature fits nicely to an exponential curve (not shown) between 160 and 298 K with a characteristic temperature $T_0$ of 154 K. The threshold currents below 160 K are higher than the fitting curve. We attribute this behavior to the same reason for the abnormal slope efficiency below 160 K. The threshold current densities at 80 and 298 K are 0.36 kA cm$^{-2}$ and 1.26 kA cm$^{-2}$, respectively. As expected, both of them are slightly smaller than those obtained from the published 30-stage structure.

The current dependent WPE at different temperatures (figure 2(b)) is created based on the data of figure 2(a). A global maximum WPE of 36% is obtained at 120 K with an operating current of 0.8 A. Not surprisingly, for currents above 0.5 A, the WPE at 80 K is lower than that at 120 K. This can be understood from the previous discussion of the $P−I$ and $I−V$ curves. Above 120 K, the WPE drops monotonically as a function of temperature with about 22% remaining at 298 K. Both the global WPE of 36% and the room temperature WPE of 22% are the highest values reported to date for all QCLs.

The best room temperature cw operation was obtained from a device epi-layer down bonded to a diamond submount. Shown in figure 3(a) are the corresponding $P−I$ and $I−V$ curves. The maximum output power reaches 3.4 W at a driving current of 1.75 A. It is noticeable that a kink appears around 1.3 A in the $P−I$ curve, which happens to be the operating current at which the WPE reaches the maximum (figure 3(b)). This kink is also present at higher temperatures in cw operation, but absent in the pulsed mode operation (figure 2), which leads us to attribute it to a signature of thermally induced mode instability. Right at the kink, the cw WPE reaches a record value of 16.5%, with 15.5% still observed in the vicinity of the kink.

The spectrum measurement was performed on a Fourier transform infrared spectrometer (FTIR) with a liquid nitrogen cooled InSb photodetector in rapid scan mode. Far field measurement was done by mounting the laser on a computer controlled rotational stage, while a liquid nitrogen cooled mercury–cadmium–telluride (MCT) detector was placed at a fixed position 30 cm away from the rotation axis. To improve the angular resolution limited by the
Figure 3. Power–current–voltage (a) and WPE-current (b) behavior of an uncoated QCL operating in cw mode at room temperature. The cavity length and ridge width were 5 mm and 8.6 µm, respectively. The device was epi-side down bonded to a diamond submount. The total output power accounts for the power from both facets.

Figure 4. Lasing spectrum (a) and far field (b) of a QCL in room temperature cw operation. The cavity length and ridge width were 5 mm and 8.6 µm, respectively. The device was epi-side down bonded to a diamond submount.

A rather big sensing area of the detector, a 200 µm slit was put in front of the MCT detector, which ensured an angular resolution of less than 0.05°. Figure 4 shows the lasing spectrum and the far field in the lateral direction. Compared with the calculated diffraction limit for a Gaussian near field with the size of the laser ridge width, the far field of the beam is clearly diffraction limited.

3. QCLs at \( \lambda \sim 10 \, \mu m \)

A lot of high power/efficiency work has been published recently for short wavelength QCLs. For long wavelength (\( \lambda > 10 \, \mu m \)) QCLs, similar developments are lacking, since the best reported average output power and cw output power in this wavelength range are 310 mW at 10.5 µm [10] and 148 mW at 10.6 µm [11], respectively. Here, we demonstrate 10.2 µm quantum cascade lasers at room temperature with 2.2 W average power and 0.62 W cw power, using a 75-stage QCL core design.
The main challenges for long wavelength QCLs are the increasing waveguide loss (roughly as $\lambda^2$) and decreasing optical confinement. Both can be, at least partially, overcome by simply increasing the number of QCL stages inside the laser core, which is similar to the argument used above at shorter wavelengths. The same thermal arguments also exist, which affects the power output as a function of laser geometry.

Our QCL structure was grown in a gas-source molecular beam epitaxy reactor. The layer structure for each QCL emitting stage was similar to that in [11], with all wells and barriers thinner by 6%. The core doping was increased by $\sim 30\%$ to achieve a higher maximum current density. Instead of a 50-stage QCL structure, we increased the number of QCL stages to 75.

The as-grown QCL wafer was processed in both double channel and buried ridge geometries. The double channel processing followed the description in [3], with a ridge width of 95 $\mu$m. Instead of using a narrow ridge width, which has low peak power, to maximize thermal conductance, we employ a thermal-load-limited approach in the long wavelength regime. In this case, the limit for the peak power is released by processing the wafer into a much wider ridge width. The buried ridge processing followed the description in [2], with a ridge width of 16.6 $\mu$m. For high average power and cw operations, advanced thermal packaging of epilayer-down bonding on diamond submounts was employed. Cleaving, bonding and testing procedures follow the description in [5]. The facets were left uncoated, with optical power collected from one facet and doubled to give the total power emitted from the device. The temperature was monitored by the thermistor of the TEC stage.

Shown in figure 5 is the low duty cycle (1%) operation of a 95 $\mu$m wide, 5 mm long, uncoated device. The heatsink temperature was changed from 298 to 373 K. Considering that the laser core is much thicker and wider than a typical QCL in the short wavelength range, we reduced the pulse width from 500 to 200 ns in order to minimize the internal heating within a single pulse. At room temperature, the threshold current density of this device is 0.88 kA cm$^{-2}$. The slope efficiency is 2.198 W A$^{-1}$, which translates to 38.4 mW A$^{-1}$ per QCL stage, compared with 21.7 mW A$^{-1}$ in [10]. The rollover current density, i.e. the current density at which the output power saturates, is increased significantly more, resulting in a much bigger dynamic operating range, hence a high peak power of 25 W. It will be shown later on that a high rollover current density is crucial for high duty cycle operation in the case of a high thermal load. The maximum WPE of this device at room temperature is 8.8% at a current density of 2 kA cm$^{-2}$. The exponential fit $J_{th} = J_0 \exp(T/T_0)$ to the threshold current density within the tested temperature range yields a $T_0$ of 140 K and a $J_0$ of 0.1 kA cm$^{-2}$ (figure 5(b)). Based on the fitted values of $T_0$ and $J_0$, the maximum operating temperature of the device can be estimated to be $T_{max} = T_0 \ln(J_{ro}/J_0)$, where $J_{ro}$ is the rollover current density. By substituting a $J_{ro}$ of 4 kA cm$^{-2}$, we have an estimated maximum operating temperature of 516 K (243°C), which provides the possibility of achieving high average power operation with a high thermal load, in which case the device stops lasing when the core temperature rises beyond the maximum operating temperature.

Figure 6 shows the measured average power performance of the double channel processed device as a function of duty cycle for two QCLs with different bonding methods. At the same duty cycle, the epilayer-down bonded device always shows a higher average power than the epilayer-up bonded one due to a higher thermal conductance of the packaging. The difference is negligible at 1% duty cycle and becomes more pronounced at higher duty cycles. For the epilayer-up bonded device, a maximum average power of 1.2 W is observed at a duty cycle of 10%. In comparison, a higher average power of 2.2 W is obtained at a higher duty cycle of 20%.
Figure 5. Temperature dependent (a) power–current–voltage (b) threshold current density of an uncoated QCL operating in pulsed mode at temperatures between 298 and 373 K. The device was processed in double channel geometry. The cavity length and ridge width were 5 mm and 95 µm, respectively. The pulsing duty cycle was 1% with a pulse width of 200 ns.

We achieved room temperature cw operation for the buried ridge processed device, which was intended to improve the thermal conductance at a much narrower ridge width of 16.6 µm. The size of the ridge width was chosen based on both thermal and optical considerations. Figure 7 shows the output power–current–voltage characteristics of a buried ridge processed device. Neither device is capable of lasing in cw mode at room temperature, which indicates that the core temperatures are well above 516 K when they are driven in cw.
Figure 6. Duty cycle dependent average power performance of two QCLs at a heatsink temperature of 298 K. The cavity length and ridge width were 5 mm and 95 µm, respectively, for both devices. The pulse width was 200 ns.

Figure 7. Temperature dependent power–current–voltage characteristics of an uncoated QCL operating in cw mode at temperatures between 25 and 45°C. The device was processed in buried ridge geometry. The cavity length and ridge width were 5 mm and 16.6 µm, respectively.

device epilayer-down bonded to a diamond submount at heatsink temperatures between 25 and 45°C. At room temperature (25°C), the maximum cw power reaches as high as 0.62 W with a cw WPE of 2.5%. The threshold current density is 1 kA cm⁻² at room temperature and 1.3 kA cm⁻² at 45°C.
4. PCDFB QCLs

At the present state-of-the-art level of 22% pulsed WPE at room temperature, extensive thermal packaging is still necessary for cw operation at room temperature. As the pulsed WPE is increased, we expect the thermal packaging to be less demanding. As the WPE saturates to a high value, the only way to increase the output optical power will be to increase the input electrical power. One can either increase the doping of the laser core to achieve a high saturation power density, or simply increase the volume of the laser core. While there are principle and practical limitations for increasing the core doping, core thickness, and the cavity length, increasing the ridge width is the easiest and has the least influence on the pulsed WPE.

At some point, broad area (ridge width greater than 50 µm) QCLs will be able to exhibit cw operation at room temperature. However, broad area QCLs with the conventional Fabry–Perot (FP) cavity suffer from a wide emitting spectrum and a broad far field profile, due to the appearance of higher order lateral modes. The PCDFB mechanism was introduced to deal with the spectral and spatial problems of the conventional broad area QCLs [12] and the first experimental demonstration of this coupling mechanism with QCLs has been realized with an output power of about 0.3 W [13].

Here, we report the performance of the next generation of PCDFB QCLs. Three PCDFB grating periods were monolithically fabricated on the same wafer and tested individually for different laser ridges. Similar to the first report, the device is based on a buried grating layer patterned by e-beam lithography and plasma etching prior to regrowth of the standard top InP waveguide cladding and cap layers used in our typical < 5 µm QCLs. Technical detail and analysis can be found in [14]. Figure 8(a) shows an SEM image of the bonded laser chip with wire bonds made to one of the emitters (laser B). The corresponding lasing spectrum from the three separate emitters is shown in figure 8(b). All three spectra show typical DFB behavior with an extremely narrow linewidth (limited by the resolution of our FTIR). The wavelengths of all three lasers agree with the designed grating periods. The mode separation for each laser corresponds to the width of the stop band arising from the index coupling, as described in [14].

Figure 9 shows the room temperature output power performance of a PCDFB QCL at 4.65 µm. The laser is driven in pulsed mode with 1% duty cycle. Peak power as high as 12 W is obtained. The ridge width and cavity length of this device are 100 µm and 3 mm, respectively. The inset of figure 9 shows the far field characteristics. The measured full-width at half-maximum (FWHM) is 2.5°, which is diffraction limited, and not current dependent above threshold.

5. QCL life testing

In addition to optimizing the power and efficiency performances, the reliability of our InP based QCLs was also investigated in high power, ambient room temperature, cw operating conditions. The devices demonstrated below began life testing in late 2005 and the initial testing results were previously reported [15]. The purpose of the experiment was to show that, similar to near-infrared (NIR) InP-based lasers, the InP-based (GaInAs/AlInAs) QCL shows very little performance degradation with time, despite a significantly higher power density. This material system benefits from the large indium atoms, which are believed to reduce the dominant degradation mechanisms such as pinning dislocation formation and propagation.
Figure 8. (a) SEM picture of a bonded PCDFB laser chip incorporation three different grating periods and (b) experimentally measured lasing spectrum corresponding to these three grating periods.

Figure 10 shows the aging curves of the currently running QCL life testing experiment, in which over 21 000 h (~2.4 years) cw operation is demonstrated. Compared with the original data, a slight performance improvement is observed, which was also seen at the beginning of testing in [15]. As reported previously, the laser cavities are 3 mm long and 11 µm wide double-channel waveguides bonded epilayer-up with indium solder to copper heatsinks. Throughout 21 000 h of testing, the lasers experienced a driving current $\geq 0.85$ A and a heat sink temperature $\geq 298$ K. Repeated power failures were experienced, which subjected the laser to additional stresses, and periodic recalibration of temperature and power were necessary to allow for drift in the testing equipment over time. Nevertheless, the lasers proved to be very robust during this process. As laser degradation was not significant in the tested lasers, more detailed, accelerated aging tests may be necessary to obtain numerical reliability projections.
Figure 9. Output power performance of a PCDFB QCL working at room temperature in pulsed mode. The inset is the far-field characteristics.

Figure 10. The power–current–voltage curves for two randomly selected strain balanced QCLs emitting at 4.8 µm, tested at the beginning of the aging experiment ($t = 0$ h) and at $t = 21000$ h. The heat sink temperature was held at $T \geq 298$ K during testing.

For future lifetesting experiments, several areas should be explored. Mirror coating are an important aspect of laser packaging, and can influence the laser threshold, output power and efficiency. The effect of laser mirror facet coating on reliability should be considered. On the one hand, the physical barrier presented by the coating may prevent contamination of the laser facet. On the other hand, degradation of the coating and parasitic mirror/coating reactions may occur at high power densities, which could potentially decrease performance. In addition, while more recent improvements have been made to laser packaging using epi-layer down indium bonding to diamond submounts, detailed life testing has not been performed as yet by our group.
6. Summary

We demonstrate efficient operation of mid-infrared QLSs at two different wavelengths, 4.8 and 10 \( \mu m \). At 4.8 \( \mu m \), WPEs high as 36 and 22% are obtained at 120 and 298 K, respectively. At room temperature in CW operation, the maximum output power reaches 3.4 W with a maximum WPE of 15.5%. At 10 \( \mu m \), watt-level average power of 2.2 W and cw power of 0.62 W are obtained at room temperature. With PCDFB mechanism, we demonstrate room temperature 12 W peak power operation at three different wavelengths around 4.7 \( \mu m \) with diffraction limited beam quality.

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