Gain-guided broad area quantum cascade lasers emitting 23.5 W peak power at room temperature

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Abstract: We report gain-guided broad area quantum cascade lasers at 4.55 μm. The devices were processed in a buried heterostructure configuration with a current injector section much narrower than the active region. They demonstrate 23.5 W peak power at a temperature of 20°C and duty cycle of 1%, while their far field consists of a single symmetric lobe centered on the optical axis. These experimental results are supported well by 2D numerical simulations of electric currents and optical fields in a device cross-section.

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References and links

Introduction
Quantum cascade lasers (QCLs) have become the sources of choice for chemical sensing and directional infrared countermeasure applications in the mid-infrared spectral range (3-15 μm).
Continuous-wave (cw) output powers up to \( \approx 5 \, \text{W} \) at room temperature have been reported [1,2]. While cw power is limited by heat dissipation due to the relatively low wall plug efficiency (\( \leq 20\% \)) [3] of QCLs, much higher peak powers can be reached in pulsed mode operation by scaling the size of the device. Broad active region configurations are interesting for QCLs, because, unlike diode lasers, they do not suffer from filamentation and, therefore, can operate stably in a single transverse mode at currents well above threshold [4]. However, if no special precaution is taken, because of the TM polarization facet reflectivity increases with mode index and broad area QCLs lase on a high-order mode with a far field profile consisting of 2 lobes propagating at large angles from the optical axis [4]. Several approaches, using photonic crystal gratings [5], angled cavities [6] and phase locked arrays [7], attempt to overcome this problem.

In this work we achieved high peak powers at room temperature in lasers operating at zero order optical mode. For this, an unusual waveguide design was implemented: active region was not etched after growth - only the cladding above was. This created a very wide active region, compared to standard QCL designs, and a narrow current injector on top. Therefore current distribution in active region became strongly non-uniform, with a decay from laser center to its sides. As active region was not etched, usual optical mode confinement by refractive index step in horizontal direction was eliminated. Instead, the gain profile corresponding to horizontal current density spread led to gain guiding and efficient optical mode selection [8].

Simulations

The effect of gain guiding was accurately simulated numerically. One symmetric half of a 2D cross-section of a QCL waveguide was used in all simulations with layer geometries corresponding to ones in fabricated devices - see Fig. 1 and section about fabrication for details. It is important to emphasize, that the depth of etching was not known precisely after fabrication; therefore, it was used as a fitting parameter. Simulations with different values of it demonstrated scaling of current density distribution width without changing its magnitude, and no qualitative changes in device physics. A value of 7 \( \mu \text{m} \), which corresponds to 1 \( \mu \text{m} \) of cladding thickness left unetched, was found to make the closest match between simulated and experimental data and therefore was used. Refractive index and conductivity values for the materials were taken from [9] and [10]. No change in simulated laser properties was observed while varying current injector width from 8 to 16 \( \mu \text{m} \); value of 10 \( \mu \text{m} \) is shown in Fig. 1.

First, the current density distributions in the whole cross-section were calculated for a range of voltages applied between top and bottom contacts. For the active region much wider than in conventional index-guided QCLs, the current density in it could not be assumed uniform anymore, and the local dependency of conductivity in growth direction on electric field was accounted for. This dependency was obtained experimentally, as proposed in [11], from a standard measurement of IV curve of a narrow ridge device with same active region design, where the current density is uniform. Even though the non-uniform conductivity added a complication of cyclic dependency of input variable on the output solution for the numerical solver, the solution still converged. The distributions of current density in the active region for a set of applied voltages are shown in (Fig. 2). They were integrated over the contacts of the laser as well to simulate the IV curve (Fig. 3).

Second, the distributions of gain as function of current density were calculated for each applied voltage. The function of gain was simulated according to [12].

Third, a boundary electromagnetic mode analysis was conducted for each distribution of gain, accounting for refractive indices of layers as well. For all voltages \( >16 \, \text{V} \), the TM00 mode is effectively confined by the gain distribution and its imaginary refractive index is higher, than for TM01, which indicates, that it also reaches the lasing threshold first (Fig. 4). Higher order modes have negative net gain \( (= \text{losses}) \) in this simulation. An example of mode electric field intensity is shown in Fig. 1. The role of gain guiding was proven by running an additional simulation.
Fig. 1. Simulated TM00 optical mode intensity (color, a.u.) and current flow (red arrows) in the center of a cross-section of a gain-guided laser (one transverse symmetric half is shown). Applied voltage is 20 V.

Fig. 2. Simulated current density lateral distribution in the active region of a gain-guided QCL as function of applied voltage (one transverse symmetric half is shown). Inset: half width at half maximum (HWHM) of current density distribution as function of applied voltage (solid curve) for 1 μm of cladding thickness left unetched as in fabricated devices. Simulations for 2 μm (dashed) and 3 μm (dotted) provided for comparison as well.
of same device geometry without gain variation; this resulted in high order mode operation. However, if then etching depth parameter was increased to reproduce the usual QCL geometry with etched active region, horizontal index guiding and zero order mode selection were observed again as expected, which became an additional proof of reliability of our model. A more precise model should have included thermally induced variation of refractive index profile during the current pulse - that, however, would dramatically increase complexity of simulations.

Finally, at 20 V applied voltage (corresponds to ≈ 14.3 A) far field of the laser was calculated based on the mode intensity distribution in the cross-section. A single gaussian-like lobe with 56° vertical and 8° horizontal full angles of divergence was obtained. While vertical angle was usual for a QCL [13], the horizontal one was few times smaller, which corresponded well to the stretched mode shape in the waveguide (Fig. 1), and what was observed later experimentally.
Fabrication

The QCL active region and top cladding were grown in a multi-wafer molecular beam epitaxy (MBE) reactor in a single growth step on n-doped substrates (InP:S, n $\approx 1 \times 10^{18}$ cm$^{-3}$). The growth started with a 1.5 $\mu$m-thick low doped InP layer (Si dopant, n $= 3 \times 10^{16}$ cm$^{-3}$). The active region consisted of 35 stages (total thickness: 1.42 $\mu$m) of a strain-balanced In$_{0.71}$Ga$_{0.29}$As/Al$_{0.75}$In$_{0.25}$As (strain: +1.18%/−1.86%) two-phonon-resonant design with a sheet carrier density per stage of 4.86 $\times 10^{10}$ cm$^{-2}$. The upper cladding layer sequence, grown with MBE, from bottom to top was: InP (Si, $3 \times 10^{16}$ cm$^{-3}$) 1.5 $\mu$m, InP (Si, $1 \times 10^{17}$ cm$^{-3}$) 1.5 $\mu$m, InP (Si, $8 \times 10^{18}$ cm$^{-3}$) 1.0 $\mu$m, InGaAs (Si, $2 \times 10^{19}$ cm$^{-3}$) 0.2 $\mu$m.

After this one of the wafers was processed in ridge-waveguide (RWG) configuration with ridge width of 12 $\mu$m for cw operation using dry etching to obtain vertical sidewalls and thick gold deposition by electro-plating for improved heat dissipation. The results obtained with this wafer were used as a reference point to evaluate the performance of the gain-guided devices.

Another wafer from the same epitaxial growth was processed in gain-guided broad area laser configuration using a process based on the one described in [14]. The upper cladding thickness was increased by growing with metalorganic chemical vapour deposition (MOCVD) additional 4 $\mu$m of layers of InP (Si) with doping concentrations increasing from $2 \times 10^{16}$ cm$^{-3}$ at the bottom to $1 \times 10^{19}$ cm$^{-3}$ at the top (layers between 9 and 13 $\mu$m of vertical axis on Fig. 1). Then the narrow current injection region was formed by etching highly conductive top cladding layers with a wet solution of HBr/HNO$_3$/H$_2$O and regrowing the insulating InP:Fe. Several different current injector widths between 10 and 16 $\mu$m were fabricated on same wafer; this parameter variation did not affect laser performance. We left $\approx 1$ $\mu$m of the low-doped ($3 \times 10^{16}$ cm$^{-3}$) cladding layer (corresponds to 7 $\mu$m etching depth mentioned in simulation). The resulting device geometry corresponded to the one simulated (Fig. 1).

Both narrow ridge-waveguide and gain guided QCLs were cleaved in 6 mm-long chips and mounted epitaxial-side up on Cu carriers with In solder. Facets were left as cleaved.

Methods and experimental results

To optimally drive these lasers with high currents and voltages (up to 20 A and 25 V) in short pulses ($\geq 20$ ns, $\approx 5$ ns rise/fall), we have developed a special pulse driver board based on fast MOSFET (metal-oxide-semiconductor field-effect transistor) driven by a dedicated gate driver (Fig. 5). Pulse amplitude was adjusted precisely with an onboard voltage regulator circuit; control of all operating parameters and pulse sequence as well as measurement of instantaneous laser current and voltage was performed by an on-board MCU (micro controller unit). The compact size of the board allowed placing it very close to the laser, thus minimizing current path length and stray inductance, which is critical for keeping current pulse edges sharp.

All the measurements were taken at room temperature (20°C) with 300 ns pulse width and 1% duty cycle unless otherwise stated. Standard LIV (light-current-voltage) curves are shown in Fig. 3. The peak power of a gain guided device reached 23.5 W at 20.4 A (limited by electronics, as laser rollover was not reached), which is over 7 times as large as maximum power of index guided one at its rollover. 300 ns pulse width was chosen as an optimal value so that, on the one hand, measurements were not affected by $\approx 5$ ns rise/fall times, and on the other - power was not reduced by heating. However, no change of LIV curves was observed for pulse widths between 60 ns and 600 ns. Wall plug efficiency at these conditions reached 11% at 1.2 A for index guided and 5.5% at 14 A for gain guided. At 20% duty cycle average total power emitted by gain guided device reached a maximum of 1.6 W. Cooling the lasers down to -30°C led to the power increase by 22% for index guided and 40% for gain guided compared to room temperature operation. Typical measured emission spectrum of the fabricated lasers is shown in Fig. 6.
Fig. 5. Top: pulsed driver simplified schematics. Vin - input voltage, 1 - laser voltage control, 2 - pulse generation, 3 - amplified pulses for driving MOSFET gate, 4 - laser voltage measurement, 5 - laser current measurement, 6 - external communication and synchronization, RS - sense resistor, AMP - operational amplifier. Solid line indicates the main current path, dashed ones - supplementary signals. Bottom: board photo, size: 88 × 33 mm.

Fig. 6. Typical measured emission spectrum of the fabricated lasers.
The output beam was characterized using a pyroelectric camera with a 124 × 124 pixel, 100 μm pitch focal plane array (FPA) and a mechanical chopper. The camera was first placed 6 mm away from the laser facet to characterize the overall beam shape and check for the presence of side lobes. In this configuration, the FPA covered an angular range of 90° × 90° with a resolution of 0.95°. Four beam pictures taken at various currents $I$ between $1.2 \times I_{th}$ and $3.4 \times I_{th}$ are shown in Fig. 7. Duty cycle had to be lowered from 1% to 0.5% when reaching $1.9 \times I_{th}$ and then to 0.4% when reaching $3.4 \times I_{th}$ in order not to saturate the camera sensor. As can be seen, the beam consisted of a single bell-shaped lobe centered on the optical axis. In contrast to index-guided broad area QCLs [4] and phase-locked QCL arrays [7], no lateral lobes propagating at large angles from the optical axis were observed. Furthermore, the beam retained its well-behaved shape up to the maximum current $I_{max} = 3.4 \times I_{th}$.

After confirming the absence of side lobes, the camera was positioned 24 mm away from the output facet, in the far field of the laser, to measure the beam divergence. The intensity values measured by the individual camera pixels were summed column by column and fitted with a gaussian line shape to determine the horizontal beam diameter (Fig. 8). Excellent agreement between the measured profile and the gaussian fit function was observed up to $2.5 \times I_{th}$. Above this value, the beam shape started to deviate from gaussian but remained single-lobe without dips. One of the reasons for that could be the thermally induced non-uniform increase of refractive index, which is stronger at higher currents and better confines modes, including high order ones. In addition, when the electric field in the active region equals and then exceeds the resonant tunneling condition, optical gain saturates and then decreases with increasing current density because most carriers are not injected into the upper laser level. This leads to a flattening of the gain spatial profile and then in the emergence of a dip in the middle of the waveguide, resulting in a weaker guiding of the fundamental mode.

Beam propagation factor M$^2$ was measured by collimating the beam with an aspheric lens ($f = 1.873$ mm) and measuring beam second moment width at different distances with same camera. In the vertical direction $M_y^2 = 1.271 \pm 0.003$, which is expectable [13]. However, in the horizontal one the precise measurement could not be obtained with the available optics due to
Fig. 8. Measured horizontal far field intensity of a gain-guided QCL at various currents (dots) along with gaussian fits (lines). Curves are shifted vertically with a step of 0.1 for distinctness. Inset: half angle beam divergence ($\theta_{d}$) at $1/e^2$ of maximum value extracted from gaussian fits with black error bars representing standard deviation errors.

the strong ellipticity of the beam, and we could just estimate the $M^2_x \approx 6$.

Additionally, a time evolution of far field profile of the beam was measured by capturing intensity variation at maximum current with a fast optical detector as a function of horizontal angle of observation (Fig. 9). The distance from laser facet to detector was 75 mm. Detector signal was captured with a fast oscilloscope synchronized with the laser pulse driver. It is clearly visible, that after first $\approx 40$ ns of the pulse, where laser was operating in a pure zero order mode, higher order modes started to contribute, which resulted in beam steering and widening. This explains a rather high value of measured $M^2_x$. Nevertheless, the laser output averaged over time, like, for example, with camera measurements described above, remained gaussian-like single lobe. Moreover, this lateral mode hopping behaviour has demonstrated a perfect pulse-to-pulse repeatability and high stability to variations of current and heatsink temperature, which could be another indication for that it is caused by thermal effects. At lower currents same pattern of beam variation was observed, but more stretched proportionally along time axis, in particular with longer operation time in zero order time at the pulse start.

**Conclusion**

We have presented a novel configuration of broad area QCLs and did their extensive characterization and numerical modelling. Compared to a standard design having same active region, larger volume of gain medium pumped by a wide current distribution in this configuration has enabled higher peak powers, while the corresponding shape of gain distribution provided efficient optical guiding. The lasers were driven with short high current pulses by a custom developed pulsed driver. They demonstrate $\approx 7$ times as high maximum power as ridge waveguide devices with same active region design. Their output beam consists of a single lobe with a ratio
Fig. 9. Top left: measured instantaneous horizontal far field intensity evolution (color, a.u.) of a gain-guided QCL during 300 ns pulse at maximum current of 20 A showing transition from TM00 to high order modes. Top right: same data averaged from 0 ns to a given time (50 ns, 100 ns, ...) shown with black dots along with gaussian fits (red lines). Bottom: half angle beam divergence ($\theta_d$) at 1/e² of maximum value extracted from gaussian fits with black error bars representing standard deviation errors.

of $\approx 1:7$ between horizontal and vertical axes, which can be efficiently reshaped into a circular one with, for instance, a pair of cylindrical lenses if required. Having such properties they can find their applications in remote sensing, night vision and directional infrared countermeasure systems.

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