Short Injector Regions for Improved Quantum Cascade Laser Performance

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Abstract: A quantum cascade (QC) laser that makes use of shortened injector regions is studied. The 3 well active region, 2 well injector region structure shows at 79 K a threshold current density of 376 A/cm^2 and a slope efficiency of 1.5 W/A. Output power is primarily limited by decoupling of the upper laser state and the lowest state in the previous active region, rather than the maximum current throughput that turns off most QC structures.

1. Introduction

Improvement in quantum cascade (QC) laser performance has been substantial in the past year, with an order of magnitude increase in wallplug efficiency and commensurate power increases being reported by multiple groups [1]. These improvements have been largely realized from more efficient thermal management, while innovation in laser design has yet to improve substantially over "conventional" QC laser designs.

One design approach that has been given little of attention so far is the concept of minimizing (or eliminating [2]) QC laser injectors. While the injector regions serve the very necessary functions of isolating the upper laser state from the continuum, providing space over which electrons can gain energy relative to the band edge, and efficiently injecting electrons into the upper laser state, the injectors do not themselves contribute to light generation. More specifically, there are three areas of primary importance to QC laser performance where minimizing injector length becomes a compelling strategy. Threshold currents decrease about linearly with decreasing the active-injector region period length. Slope efficiency also scales linearly with the number of periods within the optical mode. The effect of injector length on wall-plug efficiency η_{wp} has multiple contributions. From J. Faist [3]:

$$\eta_{wp} \propto \left[1-\frac{\tau_{trans}}{\tau_{up}}\left(\frac{\alpha_{tot}}{n_s N_p g_c}+\frac{n_{therm}}{n_s}\right)\right]$$

Clearly, wall-plug efficiency increases as the number of active-injector region periods N_p increases. However, one must also consider the active-injector region transit time τ_{trans}, which is the total amount of time required for an electron to traverse a single QC period. In fact, τ_{trans} may equally be written $\tau_{up} + \tau_{inj}$, where τ_{up} is the effective upper laser state lifetime and τ_{inj} is the time needed to travel between active regions. Certainly, most of the τ_{inj} time in a conventional QC laser is spent in the injector regions, and one intuitively gathers that a shortened injector region length would under otherwise equal circumstances lead to a shortened injector travel time. Other parameters, such as the per-period free carrier sheet density n_s, the total waveguide loss α_{tot}, per-period modal gain cross-section g_c, or thermal population of the lower laser state n_{therm} are not directly affected by injector length.

We have designed a laser that seeks to minimize injector length. Our injector region is made from only two quantum wells. With a three well active region, the entire QC structure is only five repeating quantum wells in total, as shown in Fig. 1. The design photon energy is 240.8 meV at an electric field of 128 kV/cm. The total injector region thickness, including injection and extraction barriers, is 124.5 Å and the total QC period length is 274.5 Å; for a conventional QC structure designed for similar emission energy, total period length is typically over 500 Å. Fifty periods of this structure were grown by MOCVD with an average QC active core doping density of 3.5×10^{16} cm^{-3}.

2. Laser Measurement and Discussion

Initial results are investigated for a basic ridge laser structure with a thin Ti/Au top contact and no facet coatings. Light-current-voltage (LIV) results from a single facet are shown in Fig. 2. The threshold current density at 79 K is 376 A/cm^2, and a characteristic temperature T_0 of 114 K is measured; single-facet, as-measured slope efficiency is 1.5 W/A. The laser wavelength is 5.05 µm (245.5 meV) at 80 K. Spontaneous emission from electroluminescence mesas at room temperature shows a single, dominant transition to high pumping currents.

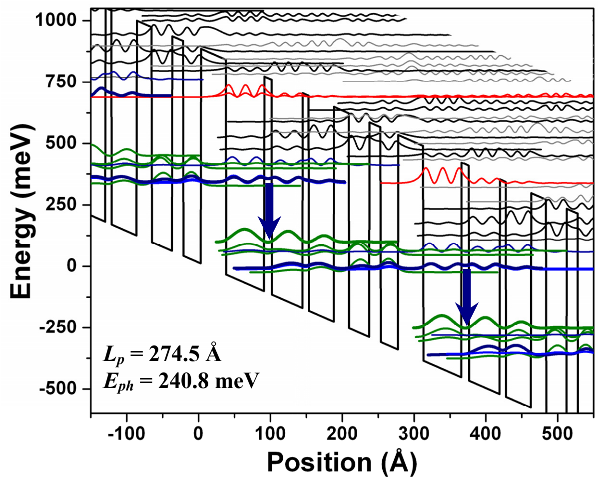

Fig. 1. The short injector QC structure. From the injection barrier the thicknesses in angstroms are (**$Al_{0.710}In_{0.290}As$** / $In_{0.638}Ga_{0.362}As$) **35** / 53 / **10.5** / 43 / **8.5** / 35 / **21** / 28.5 / **15.5** / 24.5.

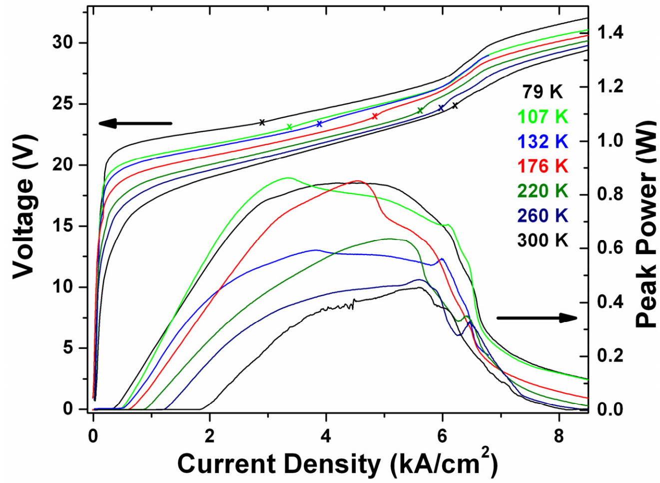

Fig 2. Light-current-voltage data for a 7.7 µm × 3 mm laser ridge.

Two physically separate mechanisms that limit light output are seen in the IV curves. For an applied 24 V, we see a small increase in differential resistance; the feature is roughly independent of temperature, and in most cases it corresponds to a drop in output power. Also, at a constant current density of about 6 kA/cm^2, a much sharper increase in differential resistance is observed. Again, this feature corresponds to a decrease in output power, in this case, turning off the laser. That one effect appears with constant applied field and the other appears with constant current density is telling of the physical origins. The current-dependent feature is the "turn-off" most commonly seen in QC lasers, where a maximum current density is reached based on the intrinsic transit times and the limited about of doping of the QC structure [3]. The voltage-dependent feature is not as commonly observed. We interpret the feature to mean that, at a certain applied field, the most rapid current transport path misaligns, forcing electrons through a slightly slower transit path, and thus increasing the differential resistance. Our laser was intentionally designed for the lowest state of one active region to be in resonance with the upper laser state of the adjacent active region at threshold, providing efficient transport between active regions and thus decreasing τ_{inj}. However, because of the spatial separation of these two states, they remain anti-crossed only over a very small field range; calculations show they are in full resonance at 128 kV/cm, and cease being anti-crossed by 130 kV/cm. The voltage-dependent feature in the IV is observed for an applied field range of about 2 kV/cm, which is consistent with the field range over which these states remain anti-crossed.

Preliminary results from buried heterostructure lasers fabricated from this material show 80 K threshold current densities of 247 A/cm^2 and slope efficiencies a factor of 3 larger than those shown in Fig 2, due to a lower loss waveguide in these experiments.

In conclusion, we present initial research on developing QC structures that minimize injector length. We have shown that in these structures, performance can be limited by misalignment of the energy levels that inject electrons into the upper laser state. Future work will focus on strategies to more robustly couple these energy states.

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