Pulsed and CW performance of 7-stage interband cascade lasers

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Abstract: We report a narrow-ridge interband cascade laser emitting at \( \lambda \approx 3.5 \mu m \) that produces up to 592 mW of cw power with a wallplug efficiency of 10.1% and beam quality factor of \( M^2 = 3.7 \) at \( T = 25 ^\circ C \). A pulsed cavity length study of broad-area lasers from the same wafer confirms that the 7-stage structure with thicker separate confinement layers has a reduced internal loss of \( \approx 3 cm^{-1} \). More generally, devices from a large number of wafers with similar 7-stage designs and wavelengths spanning 2.95-4.7 \( \mu m \) exhibit consistently higher pulsed external differential quantum efficiencies than earlier state-of-the-art ICLs.

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OCIS codes: (140.2020) Diode lasers; (140.5960) Semiconductor lasers.

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1. Introduction

By exploiting a semimetallic interface that under bias provides a unique internal source of non-equilibrium electrons and holes [1], interband cascade lasers (ICLs) emitting in the midwave infrared are able to combine the conduction-to-valence band optical transitions of a conventional diode laser with the multiple active stages of a quantum cascade laser (QCL) [2–7]. Since the first continuous wave (cw) operation at ambient temperature in 2008 [8], the ICL's maximum attainable cw output power ($P_{\text{max}}$) and wallplug efficiency (WPE) have advanced steadily. From an output of 10 mW at $T = 25 \, ^\circ\text{C}$ from the first narrow-ridge cw device, 59 mW was obtained in 2009 [9], 158 mW in 2011 [10], and 305 mW in 2012 with the introduction of a high-yield epitaxial-side-down mounting approach [11]. In 2013, a tapered ICL produced 403 mW with beam quality factor $M^2 = 2.3$ (along the slow axis, since the fast-axis beam is nearly diffraction limited) [12]. Similarly, the maximum WPEs for ICLs with 3-4 mm cavity lengths and $M^2 \leq 4$ beam qualities have progressed from 0.7% in 2008 to 3.4% in 2009, 7.6% in 2011, 8.7% in 2012, and 8.9% for the tapered laser in 2013. The highest WPE reported for an ICL is 15%, for a device with 0.5 mm cavity length [11]. Although all of the previous NRL cw devices emitted at wavelengths between 3.7 and 3.9 $\mu\text{m}$, similar performance would have been expected down to at least 3.2 $\mu\text{m}$ had narrow ridges been fabricated from existing shorter-wavelength wafers.

Some of the earlier studies also introduced corrugations to the ridge sidewalls as a means of improving the beam quality along the lateral (slow) axis [11]. This occurs because higher-order modes having greater optical intensity near the ridge boundaries are scattered preferentially over the fundamental mode. The accompanying penalty is that the corrugations typically lower the slope efficiency by $\approx 10\text{-}20\%$ due to additional scattering losses. Nonetheless, the studies to date indicate that corrugated ridges typically display higher maximum brightness figures of merit (defined below) than conventional straight-sidewall ridges [11].

In this work, we report a significant further enhancement of the maximum cw output power, wallplug efficiency, and brightness attainable from ICL narrow ridges with corrugated sidewalls. This resulted primarily from the introduction of new designs that employ both more active stages and thicker low-loss separate confinement layers (SCLs) than earlier state-of-the-art structures.

2. Design considerations

The ICL resembles many other complex systems possessing numerous design degrees of freedom, in that its best configuration can depend substantially on which performance characteristics are most critical to optimize in a given application. Much of the early ICL development emphasized minimization of the threshold input power density, in order to increase the cw operating temperatures (with ambient being the first major objective), reduce system cooling requirements, and lengthen battery lifetimes in portable systems. If low drive power is indeed the overriding figure of merit, a relatively small number of active stages is advantageous since the bias needed to reach threshold scales with $N_{\text{act}}$. For many years, $N_{\text{act}} = 5$ was the NRL norm, although now that high-temperature cw operation may be taken for granted, our simulations based on self-consistent $k\cdot p$ solutions of the assumption of a
common Fermi level extending from the hole active well of the previous stage to the electron active well of the next stage indicate that $N_{\text{act}} = 2-4$ may ultimately be ideal [6]. As the confinement factor for the active core increases, the threshold current density is expected to decrease, provided the internal loss is not appreciably increased [1,6,13].

On the other hand, the same simulations find a larger stage multiplicity to be preferable if high cw output power and brightness, rather than minimized drive power, are the primary objectives. Nominally, the slope efficiency scales with $N_{\text{act}}$, although this is accompanied by a decrease of the current at which heat accumulation in the active region causes the slope to roll over. It will be seen below that the optimal number of stages depends to a large degree on how $N_{\text{act}}$ influences the internal loss.

The net internal loss combines contributions from up to four primary sources: (1) the active gain region comprising $N_{\text{act}}$ stages layered in series, (2) the two $n$-GaSb SCLs that surround the active region, (3) the top and bottom optical cladding layers that surround the SCLs, and (4) absorption (e.g., in the dielectric coatings) and scattering (e.g., by sidewall corrugations or unintentional non-uniformities) in the narrow ridge waveguide. Since the fourth is nominally insensitive to the epitaxial layering design, it will be taken as fixed in this discussion. We also note that the various transition superlattices separating the cladding, SCL, and active regions may add a non-negligible contribution to the loss.

The analysis presented in Section III.E of Ref [1] showed that the optical confinement factors for the active and cladding layers are governed largely by the SCL thicknesses. Relatively thick SCLs are nominally advantageous, since lightly $n$-doped GaSb should exhibit low material loss. However, the active-region optical confinement factor must also remain high enough to assure adequate gain for overcoming the net losses. Whereas previous empirical studies [1] found the SCL thickness of 500 nm to be roughly optimal, in the present work we investigate whether subsequent design changes (such as carrier rebalancing [10] and increasing the stage multiplicity) and perhaps improvement of the ridge processing quality have altered the loss distribution enough to shift the optimal thickness. It should be emphasized at the outset, however, that because a greater SCL thickness tends to extract mode intensity from both the active and cladding regions, it is difficult to differentiate the relative contributions of those two regions to the internal loss in a given structure.

3. MBE growth and pulsed characterization

A series of 5-stage and 7-stage ICL wafers with carrier-rebalanced designs [10], and having both baseline (500 nm) and thicker (700-800 nm) SCLs, were grown by molecular beam epitaxy (MBE) at NRL on $n$-GaSb (100) substrates using procedures similar to those reported previously [14]. The observed performance characteristics are generally consistent for wafers grown on either a Riber Compact 21T or a Gen-II MBE system. All pulsed characterization was carried out on standard broad-area test devices with 150 $\mu$m ridge width, 2 mm cavity length, and uncoated facets.

Figure 1 plots the pulsed slope efficiencies vs. temperature for broad-area lasers processed from various 5-stage and 7-stage ICL wafers. At $T = 300$ K, the emission wavelengths ranged from 3.2 $\mu$m to 3.8 $\mu$m, the threshold current densities were 140-250 A/cm$^2$ (similar for 5 and 7 stages) and the threshold voltages were 2.3-2.9 V for 5 stages and 3.5-3.7 V for 7 stages.

The open red points represent results for two of the best wafers grown to previous baseline designs with 5 stages and 500-nm-thick SCLs. The slope efficiency is seen to decrease from 310 to 340 mW/A at 300K to 140-160 mW/A at 375 K. When the SCL thickness is increased to 700 nm (filled red points), the slope efficiency near ambient increases slightly because the loss decreases when a greater fraction of the lasing mode is moved out of the active and cladding layers and into the SCLs. However, at higher temperatures the same design modification induces a net decrease of the efficiency, accompanied by a higher lasing threshold (one of those devices did not lase at 375 K). This
probably occurs because there is no longer enough optical confinement in the active QWs to provide sufficient gain.

![Graph showing differential slope efficiencies](image1.png)

**Fig. 1.** Pulsed single-facet differential slope efficiencies above threshold for 5-stage (red) and 7-stage (blue) ICLs with both the baseline SCL thickness (500 nm, open points) and thicker SCLs (700-800 nm, filled points). All characterizations with pulse length 175 ns and repetition frequency 5 kHz were performed on standard broad-area test structures with 150 µm ridge width, 2 mm cavity length, and uncoated facets. With other design parameters held nearly fixed, results were nominally independent of emission wavelength between 3.2 µm and 3.9 µm.

![Graph showing external differential quantum efficiencies](image2.png)

**Fig. 2.** Pulsed external differential quantum efficiencies per stage (from 2 uncoated facets) at 300 K for broad-area lasers processed from wafers employing several generations of ICL designs. Gen0 devices (red circles) were designed and grown in 2008, Gen1 (green triangles) in 2008-2010, Gen2 (magenta triangles) in 2010, Gen3 (incorporating carrier rebalancing, blue boxes) beginning at the end of 2010, and Gen3B (wine stars) employing 7 stages and thicker SCLs in 2012-2013. The open blue stars are hybrid designs employing 5 stages with thicker SCLs.

On the other hand, increasing the stage multiplicity to 7 (at fixed SCL thickness) provides additional gain. Our simulations show that even though the 7-stage design with thick SCLs has 6% less gain than the 5-stage structure with thin SCLs, it benefits by reducing the mode
fraction in the cladding layers by 40%, with most of the difference being transferred into the SCLs. The observed effect is that the 7-stage devices with thicker SCLs are competitive at high \( T \) while remaining generally advantageous near ambient. This may be seen by comparing the open (500 nm SCLs) and filled (700-800 nm SCLs) blue points in the figure.

Perhaps the most important feature of Fig. 1 is that the slope efficiencies for the 7-stage devices are higher than the 5-stage values by more than a factor of 7/5, indicating that the net loss has decreased. The comparison is more direct in Fig. 2, which plots pulsed external differential quantum efficiencies per stage (from 2 uncoated facets) at 300 K for broad-area lasers processed from more than 100 wafers employing several generations of NRL ICL designs. Gen0 devices (red circles) were designed and grown in 2008, Gen1 (green inverted triangles) in 2008-2010, Gen2 (magenta triangles) in 2010, Gen3 (incorporating carrier rebalancing, blue boxes) beginning at the end of 2010, and Gen3B (wine stars) employing 7 stages and thicker SCLs in 2012-2013. The open blue stars are hybrid designs employing 5 stages with thicker SCLs. Note that for all wavelengths at which comparisons are possible, spanning 2.95-4.7 \( \mu \)m, the EDQEs are typically 5-10% higher for Gen3B designs than for Gen3. This presumably results from a successful balancing of lower modal overlap with the cladding and active regions traded off against maintaining enough active optical confinement to assure sufficient gain.

4. Narrow ridge processing and CW operation

The higher pulsed efficiencies observed for broad-area ICLs employing the new 7-stage designs with thicker SCLs appear promising for increasing the cw output power and wallplug efficiency. To confirm this, we fabricated narrow ridges from one of the 7-stage wafers, specifically that corresponding to the filled blue circles in Fig. 1, using photolithography and reactive ion etching. Although both Cl-based and BCl\(_3\)-based inductively coupled plasma (ICP) procedures were employed to fabricate ridges of several widths, we focus here on the performance of a particular ridge that employed the Cl-based ICP. A more comprehensive comparison of the two etch processes will be reported elsewhere.

The dry etching was designed to stop just below the active core of the device, in the bottom GaSb SCL, and was followed by cleaning with a phosphoric-acid-based wet etch. The ridge of width 32.4 \( \mu \)m had sidewall corrugations with a peak-to-valley amplitude of \( \approx 1.0 \) \( \mu \)m and period of 2.0 \( \mu \)m. A 250-nm-thick Si\(_3\)N\(_4\) layer was deposited by plasma-enhanced chemical vapor deposition, after which a top contact window was etched back using SF\(_6\)-based ICP. Approximately 100 nm of SiO\(_2\) was also deposited by sputtering to block occasional pinholes in the Si\(_3\)N\(_4\).

The ridge was metallized with the top contact comprised of Ag/Ti/Pt/Au (5nm/20nm/150nm/200 nm for 5 stages and 1000 nm for 7 stages) and the bottom contact consisting of Ag/Cr/Sn/Pt/Au (5nm/30nm/40nm/150nm/100nm) and then electro-plated with \( \approx 5 \) \( \mu \)m of Au. The electro-plating was patterned so as to leave non-plated gaps of \( \approx 50 \) \( \mu \)m to allow cleaving into individual laser cavities. For 5-stage ICLs, the standard metallization thickness before electro-plating was 200 nm. However, when 7-stage structures were processed by the earlier protocol and tested in CW mode, damage inevitably occurred due to excessive heating of the non-plated portion of the ridge near each facet. This was most likely exacerbated by a current runaway process that occurs in ICLs (and QCLs) with laterally non-uniform temperature distributions, because a substantial decrease of the effective series resistance with increasing \( T \) causes most of the current to flow through those regions where the temperature is highest (causing them to heat up further). Damage to the 7-stage ridges was mitigated by depositing a much thicker Au layer (\( \approx 1 \) \( \mu \)m) prior to the patterned Au electro-plating. The thicker metallization did not degrade the cleave quality, and subsequent testing confirmed that the enhanced thermal conduction prevented thermal damage to the laser (unless operated beyond the \( L-I \) rollover at much higher currents).
The device was cleaved to a cavity length of 3 mm and mounted epitaxial-side-down, using a high-yield proprietary process [11], on a C-mount attached to a thermoelectric cooler. A high-reflection (HR) coating comprised of 200 nm Al₂O₃ topped by 100 nm Au was deposited on the device’s back facet, while an anti-reflection (AR) coating consisting of a λ/4 layer of Al₂O₃ (estimated reflection =2%) was deposited on the front facet.

Figure 3 shows the ridge’s emission spectra at $T = 25 °C$ for several cw injection currents. While the centroid wavelength at the lowest current is relatively close to its value for pulsed operation ($\lambda = 3.45 \mu m$), device heating induces a red shift of up to 70 nm with increasing current.

Figure 4 plots the ridge’s cw $L$-$I$ characteristics at a series of temperatures between 15 °C and 70 °C. The maximum cw output powers of 696 mW at 15 °C and 592 mW at 25 °C are much higher than any reported previously for ICLs. Even at $T = 65 °C$, the power of 117 mW exceeds any attainable at room temperature just three years ago. The cw threshold bias voltage for the narrow ridge is 3.49 V at 25 °C, while its threshold current density of 219 A/cm² is only slightly higher than the pulsed value of 188 A/cm² measured for a broad-area device fabricated from the same wafer. The maximum cw slope efficiency of 815 mW/A exceeds the pulsed value of 601 mW/A, although that comparison is not very meaningful because the AR-coated mirror loss of the 3-mm-long cavity exceeds that of the uncoated facet in the 2-mm-long cavity.

![Emission spectra at $T = 25 °C$ for three CW injection currents. Using the centroid wavelength and the 2.3 nm/°C wavelength shift for the same device operated in pulsed mode, the temperature rise in the active region was estimated to be $\approx 36 °C$ for a current of 1.4 A.](https://example.com/image.png)
As was the case for the pulsed characteristics described in Section 3, the observed improvement goes beyond what may be associated with adding more stages to increase the slope efficiency. Equally important is the higher wallplug efficiency, e.g., 15.2% at $T = 15$ °C, that results from the redesigned structure’s lower internal loss. Figure 5 compares the CW wallplug efficiencies vs. current at $T = 25$ °C for the 7-stage ridge of this work (Gen3B) with the corresponding result for the best earlier 5-stage device with similar ridge width and sidewall corrugations (Gen3) [11]. While it is unfortunately not possible to compare devices with the same dimensions, the 7-stage ICL’s WPE advantage clearly goes well beyond that attributable to its slightly shorter cavity (3 mm vs. 4 mm). The values of 13.2% at the WPE maximum and 10.1% at the highest current compare with 8.7% and 6.5% for the 5-stage design. As discussed briefly in the introduction, the 5-stage data from 2012 in turn represented a substantial improvement over all earlier CW WPEs for ICLs with cavity lengths ≥ 2 mm. A pulsed cavity length study of broad-area devices fabricated from the wafer used to process the 7-stage narrow ridge yielded an internal loss of 2.9 cm$^{-1}$ and internal efficiency of 80% assuming an uncoated mirror reflectivity of 41%. Assuming the same internal efficiency, the 5-stage structure’s pulsed slope efficiency implies a somewhat higher internal loss of 4.1 cm$^{-1}$.
For most applications, a given laser output power is useful only in relationship to the quality of the generated beam. It is therefore useful to define a normalized brightness figure of merit (referred to below simply as “brightness”) that combines the two aspects: \( B \equiv P / M^2 \).

In the previous study of epi-side-down mounted devices with 5 active stages (Gen3) [11], this quantity was measured for ridges with both straight and corrugated sidewalls. The highest value for a straight-sidewall ridge was obtained when a maximum cw output power of 198 mW was combined with a beam quality of \( M^2 = 1.8 \), to yield \( B = 110 \) mW. The corresponding best result for a corrugated-sidewall ridge was \( P = 291 \) mW, \( M^2 = 2.2 \), and \( B = 132 \) mW.

In order to determine the “effective \( M^2 \)” [12,15,16] for the present 7-stage narrow ridge, we measured far-field intensity profiles along the slow axis for several injection currents at \( T = 25 \) °C, as shown in Fig. 6. The \( M^2 \) values derived from the profiles range from 2.5 at \( I = 460 \) mA to 3.7 at 1400 mA. It is unclear why these values are somewhat higher than those observed previously for corrugated ICL ridges of similar width [11], although one possibility is that processing differences affected the strength of the corrugation-induced scattering of higher-order lasing modes.

Nonetheless, combining the beam quality factor at the highest current (1400 mA) with the corresponding output power of 592 mW leads to \( B \approx 160 \) mW. This is higher than any previous cw brightness for a non-tapered ICL. While a recent 5-stage tapered laser achieved \( B = 175 \) mW [12], it may be anticipated that when tapered devices are processed using the newer 7-stage materials exhibiting lower loss and higher efficiency, further enhancement of the brightness will occur.
4. Conclusion

We have shown that by increasing both the number of active stages and the separate confinement layer thicknesses relative to those employed in previous state-of-the-art ICL designs, the internal loss can be reduced and lasing efficiency enhanced. For a wide range of wavelengths spanning 2.95-4.7 μm, broad-area lasers employing the new 7-stage designs consistently display 5-10% higher external differential quantum efficiencies than earlier state-of-the-art 5-stage designs.

To confirm that enhanced cw performance could also be achieved, a 32.4-μm-wide narrow ridge with corrugated sidewalls was fabricated from one of the 7-stage wafers. In cw mode, it emitted up to 592 mW of cw power at λ ≈ 3.5 μm and T = 25 °C, with a beam quality factor of $M^2 = 3.7$. The maximum cw wallplug efficiency was 13.2%, its value at the highest output power was 10.1%, and the maximum brightness figure of merit was 160 mW. All of these characteristics represent substantial advances over earlier ICL performance results.

Unfortunately, the interpretation of these findings remains largely empirical, since the available data do not allow the loss distribution, e.g., between the active and cladding layers, to be determined, or the dominant loss processes to be identified. Future studies will attempt to better understand the relevant physical processes, as a step toward identifying the most promising pathways toward further loss mitigation. At this point, there is no reason to believe that the current generation of ICLs has already encountered a fundamental limit to loss minimization or enhancement of the lasing efficiency.

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