Mid-infrared interband cascade lasers operating at ambient temperatures

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Abstract. We discuss the state-of-the-art performance of interband cascade lasers emitting in the 3–5 µm spectral band. Broad-area devices with five active stages display pulsed threshold current densities as low as 400 A cm$^{-2}$ at room temperature. Auger decay rates are extracted from the analysis of threshold current densities and differential slope efficiencies of nearly 30 lasers, and found to be significantly lower than was anticipated based on prior information. New designs also produce ICLs with room-temperature internal losses as low as $\approx 6$ cm$^{-1}$. The combination of these advances with improvements to the processing of narrow ridges has led to the fabrication of a 4.4-µm-wide ridge emitting at 3.7 µm that lased to 335 K in continuous mode. This is the highest continuous-wave (cw) operating temperature for any semiconductor laser in the 3.0–4.6 µm spectral range. A 10-µm-wide ridge with high-reflection and anti-reflection facet coatings produced up to 59 mW of cw power at 298 K, and displayed a maximum wall-plug efficiency of 3.4%.

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1. Introduction

For many decades after the first near-infrared double heterostructure and quantum well (QW) diode lasers were demonstrated in the 1970s, no semiconductor devices emitting at longer wavelengths in the 3–5 \( \mu \text{m} \) midwave-infrared (mid-IR) spectral band were capable of continuous-wave (cw) operation at temperatures high enough to permit thermoelectric cooling (\( \approx 260 \text{ K} \)). The first technology to broach the key room-temperature-cw milestone was the quantum cascade laser (QCL), which employs intersubband optical transitions in a staircase geometry that connects multiple active stages in series [1]. At \( \lambda \approx 4.6 \mu \text{m} \) [2, 3], strain-balanced InGaAs/InAlAs QCLs have achieved cw operation up to \( T_{\text{cw}}^{\text{max}} = 373 \text{ K} \) [2]. However, shifting to shorter wavelengths becomes increasingly challenging for this material system, because the strain required to maintain a sufficient conduction-band offset becomes excessive. For \( \lambda < 4.6 \mu \text{m} \), the highest reported cw operating temperature is \( T_{\text{cw}}^{\text{max}} \approx 330 \text{ K} \), and \( \lambda = 3.8 \mu \text{m} \) is the shortest wavelength for which room-temperature cw lasing has been attained [4]. While the larger conduction-band offsets in some less mature QCL materials such as InAs/AlSb [5] and InGaAs/AlAs(Sb) [6] have allowed pulsed lasing to well above ambient, it is unclear whether high-temperature cw operation will follow in view of the rather high thresholds observed to date.

In the meantime, conventional type-I mid-IR QW lasers have also reached room-temperature cw operation, but only at wavelengths a little beyond 3.0 \( \mu \text{m} \) [7–9]. Insufficient hole confinement appears to be responsible for much of the increasing difficulty at longer \( \lambda \) [8].

With a much stronger electronic confinement of both carrier types, the type-II material system based on InAs electron wells and GaInSb hole wells is a natural interband candidate for mid-IR emission [10, 11]. The interband cascade laser (ICL) [12–14], which was first proposed [15] in 1994 and is illustrated schematically in figure 1, represents an especially elegant hybrid of the conventional diode and the QCL. Even though the lasing transition in its type-II ‘W’ active region is an interband process, multiple stages can be cascaded by energetically aligning the conduction and valence states at the structure’s other type-II interface, between the electron and hole injectors. This allows electrons in the valence band to scatter elastically back to the conduction band for recycling into the next active stage. At longer wavelengths where rapid Auger decay tends to increase the current requirements, ohmic contributions to the bias voltage are usually substantial. This makes the in-series connection of the active wells in a cascade architecture advantageous over the effectively parallel current flow in a conventional multiple-QW laser. The lower current is combined with a higher bias voltage, whose minimum value is the photon energy multiplied by the number of stages.

While the first laboratory demonstration of an ICL occurred more than decade ago [16], the practical milestone of ambient-temperature cw operation was surpassed only recently when our group at Naval Research Laboratory (NRL) obtained \( T_{\text{cw}}^{\text{max}} = 319 \text{ K} \) at \( \lambda = 3.75 \mu \text{m} \) [17]. The early development was limited in part by material growth issues, coupled with an incomplete understanding of the relevant physical processes and design tradeoffs. These were compounded by the inadequacy of resources available to support ICL research (a very small fraction of those devoted to QCLs). Since NRL’s first ICL growth by molecular beam epitaxy (MBE) in 2005, progress has resulted from systematic improvements of both the MBE quality and the level of understanding of the dominant optical and electronic mechanisms. While our advanced modeling capability allows simulations to be compared in detail with laboratory data, the theoretical guidance is often combined with empirical, trial-and-error variations of the relevant design parameters.
This paper will summarize the current state-of-the-art for ICL development at NRL. It will describe both previously published performance characteristics and very recent advances.

2. Growth and processing

The five-stage ICLs described in this work were grown on $n$-GaSb (100) substrates in a Riber Compact 21T MBE system, using methods described in [18]. In particular, no attempt was made to force the interface bond type at the interfaces. The active region designs were generally similar to those described in [19, 20], except for somewhat different thicknesses and compositions of the GaInSb hole wells and other relatively minor alterations. The $n$-type doping of the InAs:Si/AlSb optical cladding layers was reduced from that in earlier 10-stage structures, in order to minimize internal losses. The first 1 $\mu$m of each cladding region next to the waveguide core was doped to $1.5 \times 10^{17}$ cm$^{-3}$, while the rest was doped to $5 \times 10^{17}$ cm$^{-3}$. Emission wavelengths were shifted by fixing the GaInSb hole well parameters while varying the thicknesses of the two active InAs electron wells that sandwich the GaInSb. The designs of samples commencing with T080828 were further altered with the specific goal of reducing the internal loss.

In order to provide rapid feedback for wafer screening and design evaluation, standardized broad-area ridges of width 70–150 $\mu$m were produced by contact lithography and wet chemical etching for pulsed characterization. The etch proceeded to a GaSb separate-confinement layer (SCL) below the active region. The mask set introduced intentional lateral corrugation of the ridge sidewalls, in order to frustrate parasitic lasing modes that can otherwise achieve feedback following strong reflections from the straight and deep-etched ridge boundaries [21]. We found that lasing in those modes can artificially suppress the observed differential slope efficiency, since the out-coupling is weak and difficult to collect due to its large angle with respect to the cavity axis. For wide ridges, the corrugations confined to several microns of the sidewalls do not appear to appreciably increase the internal loss or lasing threshold of the desired Fabry–Perot modes. The broad-area devices were cleaved to a standard cavity length ($L_{\text{cav}}$) of 2 mm.

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Narrow ridges for cw measurements were also processed from a few of the wafers. The ridges of width 4–10 µm were fabricated by photolithography and reactive-ion etching (RIE) using a Cl-based inductively coupled plasma (ICP) process that again stopped at the GaSb SCL below the active QWs. The ridges were subsequently cleaned with a phosphoric-acid-based wet etch to minimize damage from the ICP RIE process. The wet etch was observed to induce some selective undercutting of the AlSb barriers in the active region, owing to preferential etching by the phosphoric acid. A 200-nm-thick Si$_3$N$_4$ dielectric layer was deposited by plasma-enhanced chemical vapor deposition and a top contact window was etched back using SF$_6$-based ICP. Next 100 nm of SiO$_2$ was sputtered to block occasional pinholes in the Si$_3$N$_4$. The ridges were metallized and electroplated with 5 µm of gold to improve the heat dissipation. Following the division into cavities guided by cleaving lanes in the electroplated gold, high-reflection (HR) or anti-reflection (AR) coatings were in some cases deposited on one or both facets. Each device was finally mounted epitaxial-side-up on a copper heat sink attached to the cold finger of an Air Products Heli–Tran Dewar.

3. Pulsed characterization and analysis of internal loss and Auger coefficient

We obtain the most reliable information about ‘intrinsic’ device performance, uncomplicated by lattice heating and the sidewall quality of narrow ridges, by measuring the pulsed properties of broad-area lasers. The cavity-length dependence [17, 22, 23] of the pulsed differential slope efficiency then provides a determination of the internal loss and internal efficiency. In this section, we discuss a further correlation of the threshold current density ($j_{th}$) with theoretical optical gain versus carrier density to derive the carrier lifetime and Auger coefficient. However, since cavity-length measurements are too laborious to perform on a large number of samples, we will assume internal efficiencies $\eta_i$ based on those obtained from a detailed temperature-dependent investigation of the five-stage sample T080227 (listed in table 1 below) [17]. In that case, $\eta_i$ decreased gradually with increasing temperature, from 83% at 78 K to 64% at 300 K. While this assumption will affect the quantitative estimate for the internal loss, we find that the derived Auger coefficient corresponding to the measured differential slope efficiency ($dP/dI$) and threshold current density are surprisingly insensitive to the value of $\eta_i$.

We also note that the laser’s internal loss, as determined from the expression: $\alpha_i = -\ln(R)/L_{cav}[\eta_i N \hbar \omega/(2dP/dI) - 1]$, has a weak dependence on the facet reflectivity $R$. While many previous studies used a value near 30%, a more careful examination of the reflectivity problem for well-confined TE-polarized modes [24] produces a better estimate of $R \approx 40\%$. This leads to a minor upward adjustment of the Auger coefficient reported previously [19] for one of the samples treated below.

Table 1 summarizes the pulsed characteristics of five-stage ICLs fabricated from 12 representative wafers with room-temperature lasing wavelengths from 2.95 to 5.02 µm (the table does not include all of the samples characterized). Figure 2 plots the temperature dependence of threshold current densities for several samples selected from the table. In order to minimize lattice heating, the characterizations employed 100–350 ns pulses for $T \geq 300$ K, 1 µs pulses in the 150–300 K temperature range, and cw injection at the lowest temperature (where pulsed measurements are impractical due to the very low currents). The repetition rate 200 Hz for measurements up to 300 K and 50 Hz at higher $T$. The threshold current densities at 78 K were extremely low, e.g. 1.7 A cm$^{-2}$ for T080618, which makes them effectively negligible for
Table 1. Emission wavelengths, threshold current densities, threshold voltages and slope efficiencies at the indicated temperatures, along with the extracted internal losses and Auger coefficients, for five-stage ICLs fabricated from 12 different wafers.

| Sample     | λ78 K (µm) | λ300 K (µm) | jth 78 K (A cm⁻²) | Vth 78 K (V) | dP/dI 78 K (mW A⁻¹) | dP/dI 300 K (mW A⁻¹) | αi (cm⁻¹) | γ3 (×10²⁸ cm² s⁻¹) |
|------------|------------|-------------|-------------------|-------------|---------------------|----------------------|-----------|------------------|
| T080227    | 3.25       | 3.69        | 405               | 2.67        | 2.394               | 158                  | 10.8      | 4.5              |
| T080326    | 3.18       | 3.62        | 394               | 2.24        | 4.54                | 186                  | 8.7       | 4.7              |
| T080430    | 3.27       | 3.72        | 600               | 2.26        | 4.90                | 144                  | 12.1      | 7.0              |
| T080529    | 3.52       | 4.01        | 535               | 2.16        | 4.01                | 137                  | 11.7      | 5.7              |
| T080618    | 3.65       | 4.18        | 509               | 2.30        | 4.22                | 133                  | 11.6      | 5.5              |
| T080619    | 2.86       | 3.24        | 415               | 2.53        | 4.46                | 124                  | 17.7      | 3.6              |
| T080709    | 4.34       | 5.02        | 1493              | 2.68        | 2.22                | 49                   | 31.4      | 7.1              |
| T080814    | 2.63       | 2.95        | 555               | 2.81        | 4.19                | 132                  | 18.3      | 4.5              |
| T080819    | 3.91       | 4.49        | 909               | 2.78        | 3.93                | 83                   | 19.3      | 7.0              |
| T080828    | 3.22       | 3.67        | 439               | 2.50        | 6.21                | 239                  | 5.7       | 4.5              |
| T081001    | 3.23       | 3.67        | 498               | 3.08        | 5.90                | 219                  | 6.6       | 4.9              |
| T081022    | 3.24       | 3.68        | 670               | 2.39        | 6.09                | 202                  | 7.5       | 6.3              |

Figure 2. Threshold current densities versus temperature for five broad-area ICLs with 2-mm-long cavities. The measurements employed 100–350 ns pulses for $T \geq 300$ K, 1 µs pulses in the 150–300 K temperature range, and cw injection for the lowest temperatures. The line represents $T_0 = 47$ K, the characteristic temperature for T080227 over the 78–320 K temperature range.

devices producing significant optical powers. The observed variations at low $T$ are most likely due to differing densities of the traps responsible for Shockley–Read recombination.

The room-temperature thresholds of $\approx 400$ A cm⁻² for the best ICLs emitting near 3.7 µm are comparable to those measured previously for 10-stage ICLs with higher doping levels in the
optical cladding layers [23]. The threshold current densities exhibit surprisingly little variation over the 3.0–4.2 µm spectral range, which is attributable to a very weak dependence of the Auger coefficient on wavelength as discussed below. We do, however, find an increase of \( j_{th}(300\,\text{K}) \) at the longest wavelengths, e.g. \( \approx 1500\,\text{A}\,\text{cm}^{-2} \) for \( \lambda = 5.0\,\mu\text{m} \). Over the entire \( T = 78–300\,\text{K} \) range the data imply characteristic temperatures of \( T_0 \approx 37–49\,\text{K} \), although these are not the best predictors of high-\( T \) cw performance since \( j_{th} \) is governed by different non-radiative mechanisms at low and high temperatures (Shockley–Read versus Auger). Nevertheless, the \( T_0 \) values near ambient are comparable to those derived for the full temperature range, with the minor variations correlating well with the Auger coefficients deduced below.

The two primary figures of merit for achieving high-temperature cw operation are the threshold power density \( (P_{th}) \), which is obtained from the product of \( j_{th} \) and the bias voltage at threshold \( (V_{th}) \), and the rate of the threshold power density’s increase above room temperature (i.e. the characteristic temperature associated with \( P_{th} \)). Figure 3 illustrates threshold voltages versus temperature for the same samples shown in figure 2. The behavior is similar to that observed previously [23], in that \( V_{th} \) first drops as the turn-on voltage decreases (due in part to decreasing energy gap, and sometimes also to thermal activation of the carrier transport), reaches a minimum at some intermediate temperature, and then rapidly rises at high \( T \) due to the increasing ohmic contribution associated with the larger \( j_{th} \) \( (V_{th} = j_{th} \times \rho_{th} \) s, where at threshold the differential series resistivity \( \rho_{th} \) s is typically in the range 0.7–1.1 mΩ⋅cm\(^2\) at 300 K). Interband semiconductor lasers reach transparency when the bias separates the electron and hole quasi-Fermi levels by the energy gap (in each stage). The minimum required voltage is, therefore, roughly \( N \times \hbar \omega \), plus the ohmic contribution and the additional voltage of order \( k_B T \) per stage needed to overcome losses. To assess whether any other major sources of excess voltage are present in addition to these mechanisms, figure 4 plots the quantity \( V_{th} - V_{th} - N \times k_B T \) as a function of \( N \times \hbar \omega \) at room temperature for the five-stage samples listed in the table, along with other 3-, 5- and 10-stage

Figure 3. Threshold voltages versus temperature for the five samples of figure 2.
ICLs grown in 2008. It appears that the best structures require little or no additional voltage, although the ohmic term may include resistivity contributions that can be further minimized once they are better understood. Other structures require up to 0.7 V of excess bias in order to operate. Two of the worst five-stage devices in the figure were found to have inadequate Te doping in their SCLs (the SCLs may have been p-type). However, in most other cases it is unclear at present why some of the ICLs require much more voltage than others.

Figure 5 plots temperature-dependent differential slope efficiencies for the samples of figures 2 and 3. Note that the redesign of T080828 quite effectively increased the efficiency.
at both low and at high temperatures. For ICLs emitting at $\lambda \approx 3.7 \mu m$, typical $dP/dI$ values of 450–490 mW A$^{-1}$ at 78 K and 140–180 mW A$^{-1}$ at 300 K before the redesign increased to 621 and 239 mW A$^{-1}$ after. Using a fixed room-temperature internal efficiency of 64% from the cavity-length study on Sample T080227, as discussed above, the internal loss in each broad-area ICL can be estimated from its slope efficiency. Results are listed in table 1, and also plotted versus wavelength in figure 6 for these samples and a number of other 3-, 5- and 10-stage devices. For ICLs emitting near 3.7 $\mu m$, the internal loss before the redesign was as low as 8.7 cm$^{-1}$ but more typically $\approx 12$ cm$^{-1}$. After the redesign, $\alpha_i$ (300 K) decreased to the range 5.7–8.7 cm$^{-1}$. The lowest is only slightly larger than the mirror loss of $\ln(1/R)/L_{cav} \approx 4.5$ cm$^{-1}$ for the 2-mm-long cavity with uncoated facets. Taking both facets into account, $\alpha_i = 5.7$ cm$^{-1}$ implies an external differential quantum efficiency per stage of 28.3%. Figure 6 indicates little dependence on wavelength between 3.6 and 4.2 $\mu m$ (thus far the redesign has been applied only to a narrow central range near 3.7 $\mu m$). However, the measured losses increase substantially at $\lambda \geq 4.5$ $\mu m$, with $\alpha_i = 19$ and 31 cm$^{-1}$ being obtained for the ICLs emitting at 4.5 and 5.0 $\mu m$, respectively. This may reflect stronger hole absorption in the active region and/or increased free-electron absorption in the SCL and cladding regions. Curiously, the internal loss also increases at shorter wavelengths $\leq 3.4$ $\mu m$, with $\alpha_i \approx 18$ cm$^{-1}$ for $\lambda = 2.95–3.4$ $\mu m$. A photoluminescence study of wafers containing only cladding layers (no active QWs) showed trap emission in roughly this same spectral range. We therefore suspect that parasitic absorption within the InAs/AlSb superlattices may be responsible for the additional loss at shorter wavelengths.

As outlined above, the derived internal loss, measured threshold current density and calculated modal gain can be combined to estimate an Auger coefficient ($\gamma_3$) for each structure. Whereas the active energy levels of the ICL are 2D in nature, we convert to more standard $\gamma_3$ units (cm$^6$ s$^{-1}$) by assuming a typical net active QW thickness of 10 nm to normalize all sheet carrier concentrations to 3D densities. Results at room temperature are listed numerically in table 1, and are plotted versus wavelength in figure 7 for a much larger sampling of 3-, 5- and 10-stage ICLs with a variety of active-region designs. The additional data for bulk and type-I

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**Figure 6.** Wavelength dependence of the internal loss at room temperature, as estimated from the pulsed differential slope efficiencies of a wide variety of broad-area ICLs.
QW materials, and for optically pumped type-II structures, are taken mostly from [25]. Clearly, at most $\lambda$ the derived Auger coefficients for type-II QWs in ICLs are much lower than had been anticipated based on the earlier optically pumped laser and photoconductivity experiments. Furthermore, the dependence on wavelength is much weaker than was implied by the earlier work. Both of these findings are highly beneficial to the prospects for high-temperature lasers operating in the 3.0–4.2 $\mu$m window. The observed $\gamma_3$ are $4$–$6 \times 10^{-28}$ cm$^6$ s$^{-1}$ in this range, with any trends being weaker than the rather modest variations between samples. When $\lambda$ is further increased to 4.5–5.0 $\mu$m, the derived Auger coefficients increases slightly to $7 \times 10^{-28}$ cm$^6$ s$^{-1}$.

It is quite surprising (and fortunate) that the ICL Auger coefficients in figure 7 lie well below published theoretical projections [26, 27] (although some of the difference may result from the use of different gain models [28]). This cannot result from any especially optimal valence subband alignments in our active region designs, since numerous structures with a variety of GaInSb thicknesses and compositions exhibit quite similar thresholds and slope efficiencies, and hence Auger coefficients. In fact, the observation that $\gamma_3$ remains nearly constant when the hole QW thickness and composition remain fixed and $\lambda$ is varied appears to rule out any significant role for intervalence resonances (although this could reflect a substantial broadening of the resonances rather than the unimportance of intervalence processes). On the other hand, it may be significant that the present structures (along with a recent optically pumped device represented by the open star in figure 7) have much higher MBE quality than those grown more than a decade ago for the investigation of [25]. For example, defect- or interface-roughness-assisted Auger recombination may have dominated the previous lifetimes while

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**Figure 7.** Room-temperature Auger coefficient versus emission wavelength (lasers) or effective wavelength corresponding to the energy gap (other devices), for a wide variety of pulsed, broad-area ICLs from this work and [20] (solid points), along with type-I and type-II data from [25] (open points).
Figure 8. Scanning electron micrographs of a 3.5-µm-wide narrow ICL ridge that was processed by the improved etching recipe.

being much less prominent in the recent ICLs [26]. Nevertheless, further research is needed to reconcile the differences between earlier theories for Auger recombination in type-II ‘W’ QWs and the present experimental results.

4. High-temperature cw operation

We previously reported that an ICL fabricated from T080227 operated in cw mode at $\lambda = 3.75\,\mu m$ up to a maximum temperature of 319 K [17]. Subsequent narrow ridges fabricated from T080619 lased cw up to $T_{cw}^{max} = 334$ K, which is attributable primarily to the higher $T_0$ characteristic of those devices emitting at a somewhat shorter wavelength (3.3 µm). Although these first demonstrations of semiconductor lasers operating cw in this wavelength range at temperatures above ambient represent a breakthrough in mid-IR laser development, both the device designs and the processing used to etch those ridges were far from optimized.

The improved etch recipe described in section 2 has substantially reduced undercutting in the most recent narrow-ridge ICLs, as illustrated by the SEM micrographs in figure 8. This recipe was applied to sample T080828 ($\lambda \approx 3.7\,\mu m$), whose slope efficiency is the highest of all the devices listed in table 1. Electroplated ridges were fabricated with widths $w = 4.4$ and 7.0 µm (at the level of the active region), $L_{cav} = 2$ mm and uncoated facets. Figure 9 plots cw threshold current densities for the two devices at temperatures in the range $T \geq 250$ K. At $T = 300$ K, $j_{th} = 778$ and 651 A cm$^{-2}$ for the $w = 4.4$ and 7.0 µm devices, respectively, which compare to 439 A cm$^{-2}$ for the broad-area device from the same wafer. ICLs processed using the earlier etch recipe typically experienced larger degradations of the threshold current densities. The characteristic temperatures derived from these data for the 250–300 K range are $T_0 = 52–53$ K. The maximum operating temperature of 335 K for the $w = 4.4\,\mu m$ ridge is a new record for ICLs, and the highest reported for any semiconductor laser emitting in the 3.0–4.6 µm spectral range. Since this result was measured for a device with relatively short cavity and uncoated facets, further improvements in $T_{cw}^{max}$ may be expected.

Figure 10 shows cw light–current characteristics of the same two narrow-ridge devices at $T = 300$ K. The maximum cw output power for the $w = 7.0\,\mu m$ ridge is 24 mW per facet. That device’s maximum slope efficiency of 164 mW A$^{-1}$ per facet is 69% of the pulsed $dP/dI$ reported in table 1. The inset to figure 10 shows that the $w = 7.0\,\mu m$ ridge displays a maximum cw wall-plug efficiency (WPE) of 2.8% per facet at $T = 300$ K.

Additional Au-electroplated narrow ridges were processed from the same wafer to have widths of 10 µm, cavity lengths of 3 mm and coated facets. The red points in figure 11 are cw
Figure 9. Plot of cw threshold current density versus temperature for two narrow-ridge ICLs ($w = 4.4$ and $7.0 \, \mu m$) from wafer T080828. Both have cavity lengths of 2 mm and uncoated facets.

Figure 10. Plot of cw output power per facet versus injection current for the two narrow-ridge ICLs from figure 9. The inset shows the corresponding WPE facet for the wider ridge.

$L–I$ characteristics at $T = 298$ K for an ICL with HR and AR coatings, while the blue points are data for a device with one HR and one uncoated facet. Note that while the HR/U ridge has a lower lasing threshold, with increasing current the HR/AR device eventually displays slightly higher output power and WPE. Up to 600 mA the maximum powers are 59 and 51 mW for the HR/AR and HR/U devices, respectively, while the maximum WPEs are 3.4 and 3.1%. While these early efficiencies are lower than the value $\approx 11\%$ recently obtained for a 4-mm-long HR-coated QCL emitting at $\lambda = 4.6 \, \mu m^2$, they nonetheless show the promise of ICLs to perform well in the intermediate $\lambda = 3.0–4.2 \, \mu m$ spectral band. Furthermore, the input powers needed to achieve lasing are already much lower for ICLs than QCLs, due to lower threshold.
current densities and especially lower bias voltages associated with the much smaller number of stages. This can be an important consideration in field applications that require powering from batteries.

5. Conclusions

We have reviewed the state-of-art performance characteristics of ICLs emitting in the mid-IR spectral band at ambient temperatures and above. Our device development strategy relies heavily on characterizing the pulsed properties of broad-area lasers and then optimizing their designs. The most significant discovery has been that the Auger non-radiative decay rates in these type-II structures are much lower than was expected based on previous experiments and theoretical projections. Auger coefficients extracted from the lasing thresholds, differential slope efficiencies and other properties of nearly 30 lasers are remarkably consistent, and display no statistically significant dependence on wavelength in the 3.0–4.2 μm window. The $\gamma_3$ values rise only gradually beyond that, out to 5 μm. A direct consequence of the unanticipated Auger suppression is that lasing thresholds are lower than had been thought possible throughout the 3–5 μm band. Further optimization of the ICL design has reduced internal losses to as low as 5.7 cm$^{-1}$ at 300 K. In the structures studied to date, losses are lowest for wavelengths in the intermediate 3.4–4.2 μm range, but increase at both longer and shorter $\lambda$.

In parallel with the development of improved ICL designs, we have also refined the fabrication procedures for narrow-ridge devices. As a result, a 2-mm-long cavity without facet coatings achieved a record high cw operating temperature of 335 K (at $\lambda = 3.7$ μm). Another narrow ridge with HR/AR coatings produced up to 59 mW of cw output at 298 K, and had a maximum WPE of 3.4%. The structure’s flexibility provides ample opportunity for further modifications of the design space, to assure ongoing advances of the ICL performance.
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