Sb-based Interband Cascade Lasers to Cover the 3-5 μm Spectral Window


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Semiconductor laser sources for the critical 3-5 μm spectral range are evolving and improving rapidly, with significant advancements reported within the last year for three fundamentally different approaches: the intersubband quantum cascade laser (QCL), the type-I quantum well (QW) diode laser, and the interband cascade laser (ICL). Of these three, the most promising candidate to cover the entire wavelength range is the antimonide-based type-II ICL as designed and grown at the Naval Research Laboratory (NRL). Broad area devices have already demonstrated threshold power densities ($P_{th} = current\ density \times voltage$) which will enable room temperature (RT) continuous-wave (CW) operation from 2.9 out to 4.6 μm (Fig. 1). The ICL architecture appears uniquely poised not only to offer complete spectral coverage (3 – 5 μm) but also to operate with low power dissipation. Some of the most recent ICLs display $P_{th} < 0.4$ kW/cm$^2$ at 300 K ($\lambda \approx 3.6 – 4.0$ μm), which is more than 20 times lower than the best $P_{th}$ reported to date for QCLs operating at the same temperature. For this reason, the ICL approach is favored for applications demanding low power and excess heat dissipation, e.g., for long battery lifetimes in the field.

The RT threshold current densities ($j_{th}$) of the most recent NRL 5-stage broad area ICLs have been pushed below 200 A/cm$^2$, with a record best of 146 A/cm$^2$ for a device emitting at $\lambda =$

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**Fig. 1** Pulsed threshold power vs. wavelength for broad-area 5-stage ICLs at 300 K. Data are shown for several generations of NRL ICLs. The dashed line represents the estimated maximum $P_{th}$ for RT CW operation for narrow ridges.

**Fig. 2** Maximum CW operating temperatures as a function of year for NRL Type-II mid-IR lasers. Shown also are reported data from Maxion, JPL and Würzburg.
3.99 μm. Epitaxial-side-up narrow ridges fashioned from this material, with gold electro-plating for heat dissipation, operated in CW mode to 107 °C. This extends the NRL progression towards high cw operating temperatures by 35 °C, and is significantly higher than for any other interband mid-IR semiconductor laser reported to date (Fig. 2). Such dramatic improvements have been driven by the introduction of various design modifications and optimizations [patents pending] that have reduced $j_{th}$ and $P_{th}$ to values much lower than any achieved elsewhere. A short-cavity ($L_{cav} = 0.5$ mm) narrow ridge with one HR-coated facet reached threshold at 25 °C at a cw input power of only 29.6 mW, which compares to the lowest reported value for a type-I diode emitting beyond 3 μm of about 80 mW and the best QCL result of 830 mW. The substantial advantage over QCLs is attributable to the ICL’s lower current density threshold ($< 200$ A/cm² vs. $> 700$ A/cm²), and especially its lower voltage threshold (≈ 2.1 V vs. ≈ 10 V).

Narrow ridges were fabricated using a combination of dry etching by Cl-based inductively coupled plasma and a phosphoric-acid-based clean-up etch. The ridges were then electro-plated with a 5-μm-thick layer of gold. Recent work has employed two methods for obtaining narrow spectral lines corresponding to single-mode operation. First, distributed-feedback lasers were fabricated by etching 4th-order gratings into both sidewalls of the narrow ridges. For CW operation at $T = -23$ °C, up to 32 mW of single-mode output was obtained in a spectral region overlapping the strong methane absorption lines near $\lambda \approx 3.315$ μm, as illustrated in Figs. 3 and 4. Second, we also obtain single-mode output by coupling a Fabry-Perot ICL to a rectangular ring resonator. The device operating simultaneously in the Fabry-Perot and ring cavities emits in a single mode because the ring resonator free spectral range is comparable to the width of the gain spectrum. A number of different ring cavities with various ridge widths, ring widths, and rectangular ring dimensions have displayed single-mode output, with cw powers up to 5 mW.

![Fig. 3](image1.png)  
**Fig. 3** CW spectral density as a function of wavelength at $T = -23$ °C for a narrow-ridge laser with 4th-order gratings etched on both sidewalls and uncoated facets. Spectra are shown for 4 different excitation currents.

![Fig. 4](image2.png)  
**Fig. 4** Voltage and CW power as a function of current for the narrow-ridge DFB laser from Fig. 3.

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