Interband Cascade Lasers: Physical Principles and Operating Characteristics

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BIOGRAPHY

Igor Vurgaftman received the B. S. degree summa cum laude in Computer Engineering from Boston University in 1991, and the M. S. and Ph. D. degrees in Electrical Engineering from the University of Michigan in 1993 and 1995, respectively. Since 1995, Dr. Vurgaftman has been with the Optical Sciences Division of the Naval Research Laboratory, Washington, DC, where he has investigated mid-infrared lasers based on interband and intersubband transitions, methods of maintaining optical coherence in large-area semiconductor lasers, type-II superlattice photodetectors, coherent sources of surface plasmons, and spintronic optical and electronic devices, among other topics. He is the author of more than 220 refereed articles in technical journals, numerous contributed and invited talks at professional conferences, as well as 16 patents. Dr. Vurgaftman is a Fellow of the Optical Society of America and American Physical Society.

TECHNICAL ABSTRACT

The interband cascade laser (ICL) is an extremely promising midwave-infrared (mid-IR) coherent semiconductor source, which for the entire 3-6 μm spectral range has demonstrated room-temperature threshold power densities more than an order of magnitude lower than the best available results for quantum cascade lasers (QCLs) [1]. The ICL operation differs from both conventional diode lasers and QCLs, in that with the proper design a significant fraction of the carriers needed for lasing originate at a semimetallic interface located in each stage of the ICL structure [2]. If an electron injector is employed to reduce the average electric field over the stage and inject electrons into the active region, it must be heavily n-doped since most of the electrons originating at the semimetallic interface populate states in the injector [1]. While almost all of the demonstrated ICLs have employed type-II InAs/GaInSb active regions, the ICL concept can be extended straightforwardly to conventional type-I quantum wells as well as, possibly, other material systems. The presentation will review the rich physics of the ICL operation and deduce the main design principles from the existing physical constraints.

The latest experimental results will also be presented. The record cw operating temperature for an ICL emitting at a wavelength λ = 3.9 μm currently stands at 118°C. Somewhat wider (18.2 μm), 4-mm-long ridges fabricated from the same wafer with high-reflection (HR)/anti-reflection (AR) coatings on the facets emitted more than 200 mW of cw power into a nearly-diffraction-limited beam (with M2 = 1.6 estimated at the highest output power), as shown in Fig. 1. The devices were mounted epitaxial side down on a copper heat sink. Shorter-cavity (0.5-mm) ICLs fabricated from the same wafer with one HR-coated and one uncoated facet yielded a cw wall-plug efficiency (WPE) of 14.6% at room temperature (Fig. 2). This is the highest reported WPE for any interband diode operating beyond 3 μm, and is only slightly lower than the recent record value demonstrated for QCLs emitting at λ = 4.8 μm (21%). ICLs have also achieved room-temperature cw operation at even longer-wavelengths, with maximum operating temperatures of 60°C and 48°C being observed at 4.7 and 5.6 μm, respectively (Fig. 3).

The power densities required for lasing in ICLs are considerably lower than in QCLs owing to the much longer carrier lifetime (and in spite of a larger threshold carrier density). Whereas the best values demonstrated in mid-IR QCLs are just over 10 kW/cm², most recent ICL values are below 500 W/cm². Assuming similar optical cavities, this advantage translates to over an-order-of-magnitude improvement in the threshold power, with values as low as 29 mW being observed for the ICL [1]. Since most chemical sensing applications require only very low output powers, the ICL’s low threshold power implies that the lifetime, packaging, and other system requirements for battery-operated fielded systems can be significantly relaxed. Distributed-feedback ICLs are currently in development, with single-mode cw
output powers having reached tens of mW at room temperature. Based on these promising results, we expect the ICL to become the mid-IR laser of choice for those applications where compactness and low-power consumption are paramount.

![Figure 1](image1.png)

**Figure 1.** Light-current characteristics at several temperatures (left) and far-field patterns at room temperature (right) in cw mode for narrow-ridge ICLs fabricated from samples emitting at 3.7-3.9 μm and mounted epi-side-down. The estimated $M^2$ values are also shown.

![Figure 2](image2.png)

**Figure 2.** Light-current characteristics and the corresponding wall-plug efficiencies in cw mode for 15.7-μm-wide ICLs with 0.5-mm-long HR/uncoated and 1-mm-long HR/AR-coated facet emitting at 3.7-3.9 μm and mounted epi-side-down.

![Figure 3](image3.png)

**Figure 3.** Light-current-voltage characteristics in cw mode at a series of temperatures for 10.9-μm-wide 4-mm-long ICLs emitting at 4.7-4.9 μm and mounted epi-side-up.


**Keywords:** Interband cascade lasers, mid-infrared semiconductor lasers, distributed-feedback lasers, chemical sensing.

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