The Interband Cascade Laser

Subjects: Automation & Control Systems
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The interband cascade laser (ICL) has recently become the go-to coherent optical source for applications in the mid-wave infrared spectral band (especially 3–6 μm) that require high efficiency, low drive power, and small system footprint. The ICL combines a relatively long upper-level lifetime, characteristic of semiconductor interband transitions, with the voltage-efficient cascading scheme originally introduced for the quantum cascade laser (which employs intersubband transitions to produce light). Following the first room-temperature (RT) continuous wave (cw) operation in 2008, ICLs have operated in cw mode up to 118 ºC, produced > 500 mW of cw power at RT, displayed wallplug efficiencies up to 18% for RT cw operation, and operated in cw mode at RT to wavelengths as long as 6 μm. The low ICL drive power, which is 1-2 orders of magnitude less than is required for a quantum cascade laser (QCL), is especially important in applications such as portable battery- or solar-powered laser spectroscopy systems that require a small footprint. Distributed-feedback (DFB) ICLs emitting in a single spectral mode have generated up to 55 mW of cw power at RT, and have operated at wavelengths as long as 6.6 μm. Newer device classes include ICL frequency combs, interband cascade vertical-cavity surface-emitting lasers, interband cascade LEDs, interband cascade detectors, and ICLs incorporated into photonic integrated circuits.

Keywords: : interband cascade laser ; semiconductor laser ; laser design ; interband cascade detector ; single-mode laser ; vertical-cavity surface-emitting laser ; interband cascade LED ; optical frequency comb ; photonic integrated circuit

1. Introduction

The type-II interband cascade laser (ICL) has recently gained acceptance as an important coherent optical source for the mid-wave infrared spectral band (mid-IR, defined here as spanning 3–6 μm). It combines a relatively long upper-level lifetime, characteristic of semiconductor interband transitions, with the voltage-efficient cascading scheme originally introduced for the quantum cascade laser (QCL, which employs intersubband transitions to produce light). Both electrons and holes are present in each stage of the ICL's cascaded active region, even though the contacts inject and remove only electrons. The wealth of complex physics responsible for various aspects of the ICL operation have yet to be fully unraveled.

Given the volume of recent activity in the mid-IR spectral region, its technological importance requires little introduction. The most pervasive application involves the sensing of trace gases such as methane, carbon dioxide, carbon monoxide, formaldehyde, etc., in ambient air [1]. While this typically requires cw emission into a single spectral mode, low output powers on the order of 1 mW are generally sufficient. The leading military interest is for infrared countermeasure sources to jam heat-seeking missiles. Although high spectral purity is typically not needed for this application, substantial cw output powers are essential. Other potential applications of mid-IR sources include industrial process control [2], combustion diagnostics [3], clinical breath analysis [4], isotope differentiation [4], free space optical communications [5], IR scene projection [6], and the detection of explosives [7].

In spite of the mid-IR spectral band's technological prominence, until 2002, no practical coherent semiconductor source offered continuous-wave (cw) operation at ambient temperature [8]. Until then, it seemed the most straightforward route to achieving that goal was to push the well-established multiple-quantum-well (MQW) diode laser, with type-I alignment of the conduction and valence bands, to longer wavelengths by employing more strain in the layers containing Sb [9][10]. However, challenges included the rapid wavelength scaling of Auger non-radiative decay [11] and carrier escape associated with a marginal valence-band offset (VBO) in the MQWs, not to mention the general immaturity of GaSb-based growth and processing technologies.

The invention of the QCL [12][13] loomed large against this backdrop, although in its first decade a high threshold power density precluded the room temperature (RT) cw operation that is required for nearly all practical applications. Besides its high threshold current density associated with a short carrier lifetime in the upper lasing subband (≈1 ps), the QCL requires a bias of at least ≈ 10 V because 30–40 stages are needed to supply sufficient gain. Nonetheless, a modest temperature sensitivity coupled with efficient heat dissipation eventually allowed the QCL to achieve not only RT cw operation, but also cw output power above 5 W into a near-diffraction-limited beam [14][15]. There are many similarities between the cascading interband and intersubband transitions in ICLs and QCLs, but also some important distinctions that lead to very different temperature performances of the two device classes. Even though the ICL was invented only shortly after the QCL, far fewer resources have been devoted to its development over of the intervening period. This may be attributed in part to the general paucity of expertise with GaSb-based materials.

In parallel, several research groups have continued to extend the emission wavelengths of more conventional diode lasers. GaSb-based type-I MQW diodes increasingly display excellent performance over the neighboring 2–3 μm spectral window [16], and RT cw operation has been reported for wavelengths as long as 3.44 μm [17][18].

2. Evolution of the Interband Cascade Laser Concept

2.1. Initial Proposal

The first suggestion that interband transitions may be cascaded dates to a paper by Rui Yang, then at the University of Toronto, written (and reported at a conference) in 1994 and published the following year [19]. While most of the paper was devoted to a proposal that interband tunneling may be used to remove carriers from the lower lasing subband of a QCL-like device, the final figure in that work contained the first sketch of an interband cascade active core. In this first version, the composition and layer sequence of the electron injector remained unspecified, and there was no suggestion that a hole injector was needed. However, the first recognition that the QCL's very short optical phonon relaxation channel could be eliminated by substituting an interband active core was notable.

This proposal focused extensively on the use of interband transitions to efficiently extract electrons from the lower lasing subband, a necessary element of any cascading architecture that incorporates interband active transitions. The initial use of the semimetallic (SM) overlap between neighboring layers of InAs and Ga(In)Sb to ensure rapid interband transfer dates back to the resonant interband tunneling diodes (RITDs) demonstrated by the McGill group at Caltech [20], although it also bears close kinship to some slightly earlier ideas discussed by Sweeny and Xu [21]. Prior to that work, interband transfer within a device was always accomplished by heavily doping both sides of the *p-n* junction in an Esaki diode.

2.2. Improvements

While the initial paper did not use the name "interband cascade laser", it was introduced in short order by NRL researchers in collaboration with Rui Yang, who had by that time moved to the University of Houston [22]. This work introduced a single hole-injector QW into the design, noting that the active hole well by itself is unlikely to prevent excessive electron tunneling directly from the electron active well into the electron injector. Furthermore, the work extended the ICL concept to include the possibility of a type-I active region. It was pointed out that the number of wells in the electron and hole injectors could vary, as long as the total thickness was sufficient for a reasonable external field (say, 100 kV/cm) to drop a voltage of $\hbar\omega/q$, and efficient injector transport was assured.

At that time, it was unclear how strong Auger recombination would be for a type-II mid-IR QW structure, so the report limited itself to calculating the radiative current density only. A follow-up calculation by the NRL group [23] estimated a RT threshold current density (Jth), strongly dominated by the Auger process, of ~1 kA/cm^2. In fact, because the Auger coefficient turns out to be much lower than the value assumed in that paper, lasing thresholds in the 100–200 A/cm^2 range are now routinely attainable in the laboratory. Even so, that work [23] predicted that the device should be capable of RT operation. The specific design employed as many as 15 InAs QWs in the electron injector, which was too thick because the internal field was not properly taken into account. The proposed configuration had a single active InAs QW, and did not include a barrier between the electron and hole injectors.

A few months later, Vurgaftman et al. designed and analyzed a vertical-cavity surface-emitting laser with an interband cascade active region [24]. That design incorporated the so-called "W" structure with two active InAs electron wells on both sides of the GaInSb active hole well [25]. The motivation is to increase the optical matrix element and optical gain due to a stronger electron-hole wavefunction overlap. Nevertheless, since 2004 it has been a standard feature in nearly all ICL designs by the different research groups. In practice, the "W" ICL has been observed to outperform structures with a single active electron well, even after the modal gain per unit current density became much higher following other design improvements.

2.3. Early Experimental Realizations

The first successful experimental realization of an ICL was reported in early 1997 [26]. For short pulses, the device with 20 active stages operated at T = 80–120 K with a very high threshold current density of several kA/cm^2. The performance soon improved considerably, although only pulsed lasing was observed, and only at temperatures below 225 K [27][28]. It is clear in retrospect that the electron injectors in these initial ICL designs (e.g., Ref. [23]) were much too thick. Despite having 20 or more active stages, the external differential quantum efficiencies (EDQEs) per stage were low, e.g., only 6–7.5% at T = 100 K in Refs. [28] and [29]. These two working devices were the first to feature the "W" ICL configuration. Note also that by defining the EDQE as the efficiency per stage, here and below, we can directly compare the values measured for devices with a wide range of stage multiplicities (M). A slightly higher EDQE of nearly 10% at T = 80 K was soon reported [30].

Whereas the hole injectors in early ICLs had a single hole QW, a joint NRL-University of Houston publication [31] introduced the additional design improvement of incorporating a second QW, with the goal of further minimizing electron leakage straight from the active region into the electron injector. The number of QWs in the electron injector was also reduced, to eight, although the overall thickness was still high at ≈ 400 Å. The ICL with this design was the first to operate nearly to room temperature (T = 286 K) in pulsed mode. While most of the improvement probably resulted from the thinner electron injector rather than the additional well in the hole injector, the two-QW hole injector configuration subsequently became a standard feature of ICL designs.

Whereas the first structures were all grown at the University of Houston, in 1999 the Army Research Laboratory (ARL) began to grow ICLs as well. They soon improved the low-temperature EDQE per stage to ≈ 20% (> 4.5 photons emitted from all the stages for every electron injected into the device) at T = 150 K [32], although high-temperature operation was still elusive because the threshold power density remained high. Like the other early ICLs, these structures had 20–25 active stages that required a high threshold voltage approaching 10 V. Pulsed operation was observed at temperatures up to 217 K [33][34], and later 250 K [35]. Cw lasing was also achieved at temperatures up to 142 K [36][37].

The next significant milestone was the demonstration of pulsed operation at RT [38][39] by the ARL group, which by this time had spun off the company Maxion Technologies. Even though the RT threshold current density approached 7 kA/cm^2, this was tolerated by using wide ridges to manage current spreading. The devices still had 18 active stages, and the efficiency was quite low at higher temperatures. Subsequently, similar ICLs were operated up to T = 214 K in cw mode. A thick layer of electroplated Au provided heat sinking to the narrow ridge, which was etched through the active core [40]. Since the ARL/Maxion articles from this period supplied few details of the device structures, it is difficult to reconstruct the design factors that improved or limited their performance (in the context of what is now known about ICL operation).

Rui Yang's move to the Jet Propulsion Laboratory (JPL) in 2002 marked the beginning of that group's activity in the design and fabrication of ICLs. Using active regions based on the "W" configuration, they fairly soon reached RT pulsed operation and cw lasing to T = 200 K [41][42]. Their reduction of the RT Jth to ≈ 1 kA/cm^2, in an ICL with 15 active stages and emitting at λ = 3.3 μm, represented a substantial improvement over previous thresholds. Distributed-feedback (DFB) ICLs were also demonstrated [43]. The performance became considerably worse at somewhat longer mid-IR wavelengths (λ = 4.3–5.6 μm), where the maximum pulsed operating temperatures (T_{max}) were well below RT [44][45]. An ICL structure grown on a GaAs substrate suffered only a moderate performance penalty resulting from the large lattice mismatch [46].

2.4. Toward Room-Temperature cw Operation

In 2005, the JPL group demonstrated a 150 μm wide × 1.5 mm long ridge whose pulsed RT Jth was only 630 A/cm^2 [47]. This substantial reduction of the threshold allowed a 15 μm × 1.5 mm ridge to lase in cw mode up to T_{max} = 237 K at λ = 3.3 μm. These devices had a much thicker bottom optical cladding layer to prevent mode leakage into the high-index GaSb substrate, and featured only 12 stages even though the threshold voltage Vth still exceeded 6 V at RT. The addition of a thick layer of electroplated Au soon led to cw operation up to T_{max} = 264 K [48], as well as single-mode emission from a DFB ICL at a similar temperature [49]. These higher operating temperatures, in the thermoelectric cooler range, enabled JPL to qualify DFB ICLs emitting at λ = 3.27 μm for methane detection on the NASA Mars Curiosity Mission. Since 2013, the ICL-based spectrometer on Curiosity has confirmed the presence of methane on Mars, with rare bursts up to 7 parts per billion by volume [50].

The first ICLs designed, grown, processed, and characterized at NRL were reported in 2006 [51]. At that time, "W" diode lasers with similar active QWs were operating in pulsed mode at RT [52], albeit with threshold current densities well in excess of 10 kA/cm^2. The early NRL ICL designs employed "W" active regions, single-QW hole injectors, and relatively thick electron injectors with low doping in four of the wells. In fact, they were conceptually similar to the structures grown seven years earlier at the University of Houston [31], except that only 10 active stages were employed and the hole injector comprised a single QW. The initial RT *J*th of 7 kA/cm^2 was quite high, being only a little lower than for the "W" diode lasers. NRL reported a cryogenic DFB ICL based on this structure [53].

In the next round of NRL designs, the number of stages was reduced to $M = 5$ [54] in order to lower the threshold power density. Simulations had determined that the gain per unit current density is actually quite high in an ICL, e.g., much higher than in a QCL that typically requires 30 or more stages to realize low *J*th at RT. Although the pulsed RT *J*th at the emission wavelength of λ = 3.7 µm still exceeded 2 kA/cm^2, a 12 µm wide × 3.9 mm long Au-electroplated ridge fabricated from this material operated cw to T_{max} = 257 K, a little lower than the best JPL result at the time [55].

Subsequently, NRL reported a series of advances in such key performance figures of merit as *J*th, *P*th, and EDQE, at and above RT. While the design modifications responsible for these improvements did not appear in the journal publications from the period, they were later disclosed in a series of patent applications. One of the first changes was to employ a much thinner (200–250 Å) electron injector, which allowed operation at a higher external electric field. In conjunction with the double-QW hole injector originally attempted in 1998 [31], this enhanced the electron occupation of the active region while reducing somewhat the electron density in the electron injector [56]. The result was a lower RT threshold current density of 1.15 kA/cm^2 for a ten-stage structure. A narrow, Au-electroplated ridge fabricated from that wafer operated cw to T_{max} = 269 K [57]. A cavity-length study found that the internal loss increased rapidly with temperature, e.g., to α_i = 28 cm^{-1} at T = 275 K [58]. A gain per unit current density of 4 cm/kA/stage was determined at the same temperature.

In 2008, an NRL ICL emitting at λ = 3.75 µm achieved RT cw operation [59]. Several additional design improvements contributed to this milestone: (1) the number of stages was reduced to five, to further lower the threshold power density; (2) two n^--doped GaSb separate-confinement layers (SCLs) were introduced on both sides of the active core; (3) the doping of the cladding regions immediately adjacent to the SCLs was reduced, to 1.5 × 10^{17} cm^{-3}; (4) the AlSb barrier between the electron and hole injectors was thickened, to 20 Å, along with several other minor modifications. As a result, the pulsed *J*th at RT dropped to ≈ 400 A/cm^2, the lowest value reported for an ICL up to that point. While some of the improvements were anticipated based on general design principles for semiconductor lasers, it was not obvious that an optimized 5-stage ICL could maintain approximately the same *J*th as a 10-stage device.

3. High Performance and New Device Classes

Subsequent advances have included operation in cw mode up to 118 ºC [60], the production of > 500 mW of cw power at RT [61], wallplug efficiencies up to 18% for RT cw operation [62], and operation in cw mode at RT to wavelengths as long as 6 µm [63][64]. The low ICL drive power [65], which is 1-2 orders of magnitude less than is required for a QCL, is especially important in applications such as portable battery- or solar-powered laser spectroscopy systems that require a small footprint.

3.1 Single-Mode ICLs

Distributed-feedback (DFB) ICLs emitting in a single spectral mode have generated up to 55 mW of cw power at RT [66], and have operated at wavelengths as long as 6.6 µm [63]. Nanoplus currently offers DFB ICL products at wavelengths spanning 3-6 µm [67]. Thorlabs Quantum Electronics recently reported a novel narrow ridge architecture [68] that alternates regions with corrugated sidewalls (to suppress higher-order lateral modes) [69] with regions having a top DFB grating. At λ = 3.3 µm, the resulting lasers generated up to 42 mW of cw power at RT in a single spectral mode.

3.2 Interband Cascade Vertical Cavity Surface Emitting Lasers (ICVCSELs)

NRL recently demonstrated ICVCSELs operating at λ ≈ 3.4 µm [70]. A distributed Bragg reflector (DBR) mirror formed by 22.5 repeats of GaSb/AlAsSb provided the bottom mirror for a cavity that included 15 interband cascade stages split into three groups positioned at the antinodes of the optical field, while the top mirror was formed by a 4-period Ge/Al_2O_3 DBR. The ICVCSELs operated in pulsed mode to 70 °C, with circularly-symmetric outputs and RT threshold current densities as low as 390 A/cm^2. However, the differential slope efficiencies were low due to loss in the top and bottom mirrors, and mode overlap with the annular top contact. The smallest device (20 µm aperture diameter) operated in a single spectral mode. Although a mid-IR VCSEL reported by the Walter Schottky Institut operated cw up to -7 °C for emission at λ = 4.0 µm, their diode structure employed multiple type-II "W" quantum wells rather than interband cascade stages [71]. Using optical pumping of a type-I gain region, Praevium and Thorlabs recently demonstrated a VCSEL whose single-mode center wavelength of 3.35 µm could be tuned by 97 nm via positioning of an external top mirror with a micro-electromechanical system (MEMS) [72]. Cw operation was observed up to 20 °C. The same team quite recently demonstrated an electrically-pumped ICVCSEL (λ = 3.35 μm) that operated in cw mode to 26 °C. At *T* = 16 °C, the threshold current was 6 mA, and 70 μW of single-mode cw output was produced [72]. The longer-term objective is to produce MEMS-tunable ICVCSELs.mm.

3.3 Interband Cascade Light Emitting Devices (ICLEDs)

NRL also recently demonstrated ICLEDs [73], which for emission at a peak wavelength of λ ≈ 3.2 μm displayed higher maximum output powers, radiances, and efficiencies than any earlier mid-IR LEDs. A novel design that positioned 22 active stages at antinodes of the optical field reflected by the metal mirror produced up to 2.9 mW cw from a 400 mm diameter mesa at RT. Subsequent devices emitted > 1.3 mW at a peak wavelength of 4.1 μm and > 0.4 mW at a peak wavelength of 4.7 μm when operated cw at RT [74].

3.4 Interband Cascade Laser Frequency Combs

Jet Propulsion Laboratory and NRL recently demonstrated the first ICL frequency combs [75]. The inherent nonlinearity of the ICL medium supports self-starting broadband comb generation with low electrical power consumption (< 1 W) at RT. Furthermore, ICL combs with sub-MHz free-running optical linewidth yielded dual-comb spectroscopy (DCS) in the 3-4 μm region [76]. A team led by TU Wien subsequently reported active mode locking [77] and a monolithic platform that combined an ICL frequency comb with an interband cascade detector (ICD) [78]. JPL and NRL also combined frequency combs and ICDs processed from the same wafer material [79]. SUNY Stony Brook recently demonstrated passive mode-locking at λ = 3.25 μm using a 3-stage type-I ICL [80].

3.5 Photonic Integrated Circuits (PICs) Incorporating Interband Cascade Lasers on Silicon and III-V Platforms

Mid-IR PICs compatible with existing Si photonic and electronic technologies promise to enable low-cost, compact sensing systems. NRL, UCSB, and U. Wisconsin previously reported the heterogeneous integration on Si of Fabry-Perot and DFB QCLs operating at 4.8 μm [81]. UCSB and NRL more recently demonstrated the integration of ICLs emitting at λ ≈ 3.6 μm on silicon-on-insulator (SOI) waveguides [82]. In pulsed mode, a device with an 11-μm-wide III-V mesa on top of a 1-μm-wide silicon waveguide emitted > 6 mW at RT, and operated to 50 °C even though most of the injected current was lost to sidewall leakage that resulted from non-optimal processing.

Whereas silicon-based PICs may ultimately span the uv to longwave IR spectral bands, some applications that do not require multi-spectral operation may benefit from the simpler and more straightforward processing of devices on the native III-V substrates. NRL recently proposed a flexible III-V PIC architecture that flexibly combines ICLs, ICDs, passive waveguides, and other optical components on a GaSb platform, or analogous QCL-based devices on an InP platform [83].

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