Recent progress in development of mid-IR interband cascade lasers

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ABSTRACT

Type-II interband cascade lasers are promising in becoming efficient and compact mid-infrared (3-5 μm) light sources for many applications. Significant progress toward such a goal has recently been made in terms of lowering their threshold current densities (e.g. ~9 A/cm² at 80 K) and raising operation temperature (e.g. 325 K in pulsed and 200 K in cw modes). Also, continuous wave operation of single-mode distributed feedback interband cascade lasers has been demonstrated. We review the recent progress of the Sb-based mid-IR interband cascade lasers and present some latest results.

Keywords: mid-infrared, lasers, semiconductors, quantum wells

1. INTRODUCTION

Compact and reliable mid-infrared sources are needed to meet the growing demand for many military and civilian applications such as infrared countermeasures (IRCM), chemical warfare monitoring, IR ladar, free space communications, medical diagnostics, and gas sensing. Because of considerable advantages in terms of cost, volume, weight, simplicity of design, reliability, and overall performance, efficient mid-IR semiconductor diode lasers are desirable. Requirements for such lasers include a relatively high output power and continuous wave (cw) operation either at ambient temperature or at temperatures accessible with thermoelectric (TE) coolers. Antimonide-based type-II interband cascade (IC) lasers, that take advantage of characteristic band alignments in type-II quantum well (QW) heterostructure to form cascade stages for photon emission with interband transitions [1], can have high quantum efficiency and are promising in meeting requirements of many practical applications. Theoretical calculations [2,3] also projected the feasibility of IC lasers to operate in cw mode up to room temperature with high output power.

Following the proposal of IC lasers in 1994 [1] and stimulated by the theoretically projected high performance of type-II IC lasers [2-3] and remarkable advances of intraband quantum cascade (QC) lasers [4-6], experimental efforts toward developing high-performance type-II IC lasers started in 1995 and have achieved significant progress with the use of three molecular beam epitaxy (MBE) systems. The successful growth of IC laser samples in different MBE systems at three laboratories (i.e. Riber 32 at the University of Houston, Varian Gen-II at the Army Research Laboratory, Applied-EPI Gen-III at Jet Propulsion Laboratory) confirmed the general principle and concept of IC lasers. Reviews of early work on type-II IC lasers made from the first two MBE systems were given in references [7] and [8]. In this paper, we review the recent progress made at Jet Propulsion Laboratory (JPL) [9-12] and present some of our latest results.

2. EXPERIMENT

Sb-based IC laser samples were grown in a solid source Applied-EPI Gen-III MBE system generally on unintentionally doped p-type GaSb (001) substrates. The IC laser structures are composed of multiple coupled QWs made from Al(In)Sb, InAs, and Ga(In)Sb layers [9-12] and have cascade stages ranging from 15 to 28 depending on the emission wavelength. Thick InAs/AlSb superlattices were usually employed as the bottom and top cladding layers. The active region is comprised of asymmetric AlSb/InAs/GaInSb/InAs/AlSb multiple coupled QWs, having a relatively large wave-function overlap between two interband transition states with an enhanced optical gain similar to the W-structure [13, 14].

After growth, the samples were usually processed into broad-area mesa-stripe lasers with metal contacts on the top n-type layer and the bottom p-type substrate. Laser bars were cleaved to form cavities 0.5 to 1.5 mm long with both facets left uncoated. The laser bars were affixed with indium, epilayer side up, onto a copper heat-sink and was then mounted on the temperature-controlled cold finger of an optical cryostat. A thermopile power meter was used to calibrate the cooled InSb detector used in our measurements and to measure the optical output in cw mode. It should be
noted that the power measurements reported below are conservative where only 10% loss from the transmission through the optical cryostat window was assumed without accounting for beam divergence and other factors. The emission spectra were obtained by focusing the output beam onto the entrance slit of a 0.55-m monochromator or a Fourier Transform infrared (FTIR) spectrometer. In pulsed mode, current pulses of 1-μs duration and 1 kHz repetition rate were injected into all laser devices at various temperatures.

3. RESULTS AND DISCUSSION

3.1 15-stage interband cascade lasers near 3.2 μm

Two laser samples, labeled J134 and J137, were grown with 15 cascade stages for photon emission near 3.2 μm [10] and were processed into deep etched mesa stripe lasers. A 150-μm-wide and 0.8-mm-long laser made from J134 operated at temperatures up to 150 K in cw mode and up to 325 K in pulsed mode. Its pulsed lasing spectra is shown in Fig. 1 in the wavelength (λ) range from ~3.03 to 3.27 μm. The lasing wavelength red shifts when the temperature was raised from 100 to 325 K. At certain temperatures, there could be two or three emission peaks separated by ~23 to 24 nm (<4 meV in energy scale) well within the bandwidth of a typical gain spectrum. These peaks were divided into different groups as summarized in Fig. 2 for both pulsed and cw modes. At low temperatures, the shorter wavelength group appeared first when the threshold was reached. The increase of the temperature led to inter-group hopping of the laser mode as marked by the arrows in Fig. 2. In other words, a mode from the longer wavelength group became dominant or emerged first when the temperature was raised to certain levels. The mode grouping is related to gain/loss modulation at a period inversely proportional to the substrate thickness due to optical mode leakage into the high index substrate and interference between the waveguide and substrate modes [15, 16]. Within each group, the wavelength shift rate (dλ/dT) with temperature is ~0.9 nm/K. The rate (dλ/dT) is smaller than the band-gap change of the constituent bulk materials (e.g. InAs) and the wavelength temperature coefficients for optically pumped type-II QW lasers [17] and type-I QW diode lasers [18]. This is attributed mainly to the increased electric field in the active region with the larger threshold voltage at high temperatures, which causes blue shifts for two spatially indirect transition states as observed previously from IC emitting diodes [19] and thus partially offsets the red shift of the decreased band-gaps of the constituent bulk materials.

![Fig. 1 Pulsed lasing spectra from a 150-μm x 0.8-mm mesa stripe laser at temperature range from 100 to 325 K](image)

Lasers with different mesa widths on the same bar were fabricated from J137 [10]. A 110-μm-wide and 1-mm-long mesa stripe device lased in cw mode at heat-sink temperatures up to 175 K at ~3.25 μm. The maximum cw operation was limited by a significant amount of heat generated in the 110-μm-wide mesa stripe laser at elevated temperatures. With a narrower width of 30-μm, a device on the same laser bar was able to lase in cw mode with notable output power.
at heat-sink temperatures up to 200 K near 3.27 μm as shown in Fig. 3. This was due to the reduction of total heat generated with the lower threshold current when compared to wider-mesa stripe lasers. This 30-μm-wide laser also operated in pulsed mode at temperatures up to 315 K and its lasing wavelength is about 3.34 μm at 310 K as shown in the inset of Fig. 4. As summarized in Fig. 4, these lasers exhibited threshold current densities lower than any previously reported mid-IR lasers in a wide temperature range. For example, a threshold current density of ~8.9 A/cm² was observed from a 110-μm-wide laser at 80 K, and the cw threshold current density of 30-μm-wide laser at 200 K was 205.5 A/cm². With such low threshold current densities, it is possible to have these lasers operate in cw mode at temperatures significantly higher than 200 K. According to the extracted specific thermal resistance of ~14 K·cm²/W for the 30-μm-wide laser, the theoretical estimation of the maximum cw operating temperature is 201 K in good agreement with the experimental value of 200 K. If the specific thermal resistance can be reduced to 2 K·cm²/W with an even narrower stripe laser and improved device fabrication/packaging, the theoretical maximum cw operating temperature would reach 285 K based on the threshold characteristics in Fig. 4. Considering the possible increase of threshold current density with conceivable effects such as surface recombination and leakage on narrower devices, the actual maximum cw operating temperature may not reach 285 K by improving device fabrication/packaging alone, but will likely be raised to the temperature accessible by TE coolers (>230 K).

3.2 23-stage interband cascade lasers near 4 μm

Several laser samples were grown with 23 cascade stages for photon emission near 4 μm as described in details in Ref. [9]. A broad-area (150 μm×1-mm) deep etched mesa stripe laser made from sample J165X operated at temperatures up to 145 K in cw mode and up to 300 K in pulsed mode. Its current-voltage-light characteristics are plotted in Fig. 5, showing significant peak power obtainable in the temperature range from 150 to 290 K. At 300 K, the device lased near 4.1 μm as shown in the inset of Fig. 5, demonstrating the longest wavelength room-temperature III-V interband diode laser.

In additional to the broad-area deep etched mesa stripe lasers, shallow-etched narrow (15-20 μm-wide) stripe ridge lasers were made from sample J171X. Fig. 6 shows current-voltage-light characteristics and differential resistance (dashed curves) of a shallow-etched 0.5-mm-long mesa-stripe laser in cw mode. Its etching depth is about 2 μm and extends into only two stages of the cascade region. Hence, its differential resistance and its voltage are initially much smaller than those of a deep-etched mesa stripe laser in a considerable current range before the threshold. Consequently, its characteristics are much like those of a gain-guided metal stripe laser with relatively high threshold current due to significant current spreading in the lateral direction. When the mesa etching was deepened to ~2.9 μm (extending into
14 cascade stages), the current spreading was suppressed substantially and the threshold current was reduced by about an order of magnitude, leading to cw operation temperatures up to 145 K with an emission wavelength of ~4.035 µm.

![Fig. 5. Current-voltage-light characteristics of a 150-µm-wide and 1-mm-long mesa-stripe laser in pulsed mode and its lasing spectrum (inset) at 300 K.](image5)

![Fig. 6. Current-voltage-light characteristics and differential resistance (dashed curves) of a shallow-etched 0.5-mm-long mesa-stripe laser in cw mode.](image6)

3.3 28-stage interband cascade lasers in the 4.3-4.7 µm wavelength region

A laser sample J243 was grown with 28 cascade stages for photon emission in the 4.3-4.7 µm and was processed into deep etched mesa stripe lasers [12]. A broad-area (150 µm x 1-mm) mesa stripe laser operated in cw mode at temperatures up to 110 K with emission wavelengths from ~4.3 to 4.5 µm as shown in Fig. 7. The output power of this laser exceeded 30 mW/f at 90 K with a threshold current density of 41 A/cm². The threshold current densities are higher than the observed values for our IC lasers at shorter wavelengths, but are the lowest ever reported for diode lasers operating in such a long wavelength region. The threshold voltage is 9.04 V at 80 K which is only about 1 V higher than the minimal required bias voltage (8.05 V, determined by the number of cascade stages times the photon energy in eV), indicating the efficient use of bias voltage in the IC laser. Under pulsed conditions (1 µs current pulses at 1 kHz), this laser was able to operate at temperatures up to ~237 K with emission wavelength extending to 4.7 µm as shown in the bottom of Fig. 7. To our knowledge, there was no III-V interband diode laser in the literature that can operate above 150 K at wavelengths beyond 4.5 µm. The significantly higher temperature operation of this laser suggests great potential in extending type-II IC lasers to an even longer wavelength region.

Threshold currents and voltages as a function of the heat-sink temperature are summarized in the top of Fig. 8. Measurements for a second 150-µm-wide device from the same laser bar show slightly lower threshold current densities (e.g. ~28 A/cm² at 80 K) at low temperatures, but slightly higher threshold current densities at the higher temperatures in cw mode. The difference becomes relatively significant at high temperatures in pulsed mode with high currents, due partially to variations in material uniformity and device fabrication, as well as fluctuations/uncertainties with circuit ringing under pulsed conditions during the experiment. The threshold current in cw mode shows a larger deviation from an exponential increase with temperature. This behavior is attributed to substantial heating of the active region, which illustrates the need to decrease specific thermal resistance in order to further improve device performance. The specific thermal resistance $R_{th}$ can be estimated from the data in Fig. 8 by comparing the difference in temperature between a pulsed and cw mode operation with equal threshold voltage and current density [20, 21]. The estimated specific thermal resistance for the devices is about 25-30 K · cm²/kW, comparable to the values (~24-29 K·cm²/kW) reported for previous broad-area IC lasers with 18 stages [22], but much higher than values reported for narrow-stripe intraband QC
lasers (−2−2.4 K cm²/kW epi-side-up [21], −0.33−0.9 K cm²/kW epi-side-down [23]) and for epi-side-down mounted broad-area type-II QW mid-IR lasers (≤2 K cm²/kW for optical pumping [17]).

The large difference in maximum operation temperature in pulsed and cw modes for the 150 μm-wide stripe mesa lasers signifies the high specific thermal resistance of 25−30 K cm²/kW as the limiting factor on laser performance. A deep-etched narrow mesa stripe (20 μm-wide and 1-mm-long) device fabricated later from the same sample operated in cw mode at higher temperatures up to 125 K at an emission wavelength of 4.56 μm as shown in the bottom of Fig. 8. However, this 20 μm-wide laser exhibited higher threshold current density, which was caused mainly by high current leakage associated with imperfections in device fabrication. Further increase in the cw operating temperature is therefore restricted. Nevertheless, this laser operated in pulsed mode at temperatures up to 240 K, comparable to 237 K achieved from 150-μm-wide lasers, indicating negligible optical loss from etched surfaces on the narrow stripe laser. The specific thermal resistance extracted from Fig. 8 is −7.9 K cm²/kW at 125 K. This value is significantly lower compared to the specific thermal resistance of the 150 μm-wide stripe mesa lasers. With improved device fabrication to reduce current leakage, cw operation temperature can be significantly increased towards temperatures obtainable by thermoelectric coolers. Other techniques such as mounting the laser device epilayer-side down and applying metal coatings to facilitate heat transfer will also allow the laser to operate at higher temperatures.

3.4 Thin top-cladding IC lasers and distributed feedback lasers

In the above, all the IC lasers employed a thick InAs/AlSb SL top cladding layer (>1.2 μm). In order to facilitate the integration of distributed feedback (DFB) gratings into the laser structures without the need for deep etching to increase
the coupling coefficient to a significant value, we have developed a thin top-cladding (~0.3 \( \mu m \)) IC laser with 18 cascade stages [11]. The top metal contact, however, will be close to the active region and therefore will introduce a larger waveguide loss. To minimize this loss, SiO\(_2\) layers were deposited onto the sidewalls of the mesa stripes and metal contacts were connected to the top edges of the mesa stripes as employed previously for an intraband QC laser design [24]. Since the top n-type InAs contact layer is an excellent conductor and the in-plane conductivity is significantly higher than in the growth axial direction at the InAs/AlSb SL, superior lateral current injection and distribution throughout the device are expected.

Two laser samples J173 and J241 were grown on a GaSb (001) substrate for photon emission near 3.4 \( \mu m \) and 3.5 \( \mu m \), respectively. Both samples were first fabricated into mesa stripe lasers (without DFB grating) with metal contacts on the top edges of the mesa stripes and bottom substrate. Arrays of 1-mm cavity length lasers of various stripe widths were cleaved from the two samples and later mounted epi-layer-side up onto a Cu-block for characterization. A 30-\( \mu \)m-wide Fabry-Perot (FP) laser made from J241 operated in cw mode at temperatures up to 180 K covering wavelength range from ~3.5 to 3.64 \( \mu m \). The FP devices made from J173 with mesa stripe widths of 110, 50, and 30 \( \mu \)m lased in cw mode at temperatures up to 165, 175, and 190 K, respectively, with wavelengths near 3.4 \( \mu m \). The higher cw operation temperature with the narrower mesa was due to the reduction of total heat generated with the lower threshold current when compared to the wider-mesa stripe lasers. Fig. 9 shows current-voltage-light characteristics of a 30-\( \mu \)m-wide and 1-mm-long mesa stripe laser (made from J173) at a heat-sink temperature range from 80 to 185 K. Significant output power (>60 mW at 80 K; ~0.7 mW at 185 K) was obtained from the device. At 80 K, the threshold current density was ~15 A/cm\(^2\) for the 110-\( \mu \)m-wide device, ~18.6 A/cm\(^2\) for the 50-\( \mu \)m-wide device, and ~28 A/cm\(^2\) for the 30-\( \mu \)m-wide device (Fig. 10). The relatively higher threshold current density for the narrower mesa stripe width devices was caused mainly by the significant current spreading as a result of a shallower etching (~1.55 \( \mu m \)) that does not give a deep enough mesa structure to confine current in all 18 cascade stages. Nevertheless, the 30-\( \mu \)m-wide mesa stripe laser was able to operate in pulsed mode (with 1 \( \mu \)s current pulses at 1 kHz) at temperatures up to 310 K with a lasing wavelength \( \lambda \) of about 3.53 \( \mu m \) (Fig. 10). It has the highest operation temperature among III-V diode lasers at this wavelength, which indicates the insignificant effect of the thin (~0.3 \( \mu m \)) top-cladding on device performance when compared to thick top-cladding IC lasers.

![Fig. 9. Current-voltage-light characteristics of a 30-\( \mu \)m-wide mesa-stripe laser and its cw lasing spectrum at 185 K.](image1)

![Fig. 10. Threshold current density of three mesa stripe lasers (made from J173) and the lasing spectra of the 30-\( \mu \)m-wide laser in pulsed mode (inset).](image2)

The high-resolution emission spectrum of the device at 185 K (inset of Fig. 9) shows constructive and destructive interference patterns of optical modes within a 1-mm long FP cavity. The separation \( \Delta \lambda \) between adjacent oscillations is 1.6 nm. If this value of \( \Delta \lambda \) is used in estimating the effective index \( n_{eff} \) of the optical mode according to \( \Delta \lambda = \lambda^2 / (2n_{eff}L) \)
where $L$ is the cavity length, the effective index could be as high as 3.68 at 185 K. The effective index of 3.68 extracted from the oscillation pattern is significantly larger than the calculated value of ~3.4 for a waveguide mode confined mainly in the cascade stage region. The existence of many lateral modes could cause the overestimation of effective index to certain degree based on the oscillation pattern, but would not account for such a significant difference. We found that the effective index extracted from the oscillation pattern for every IC laser examined by us could vary from 3.44 to 3.73 depending on the temperature and devices. This suggests substantial coupling of optical modes between the waveguide and high index (~3.8) substrate (~90-140 µm) with considerable photon leakage from the waveguide (cascade region) to the substrate and the reflection back from the substrate, which is related to temperature-dependent emission wavelength. Hence, the observed oscillation pattern is a collective representation of many modes including some that consists of a significant fraction of the substrate mode, making it difficult to use the pattern for accurately extracting the effective index of a single mode in the waveguide.

Considering some uncertainties of effective index, DFB gratings with different periods were patterned on sample J173 by etching through the top 35 nm thick InAs contact layer and into the top InAs/AlSb SL cladding layer with a total etching depth of 100-120 nm. The DFB lasers were then processed into ~1.5-µm-deep mesa stripes with widths of 30, 50, and 110 µm and cleaved into 1.5 mm-long cavity with both facets left uncoated. Fig. 11 shows the cw current-voltage-light characteristics of a 50-µm-wide mesa stripe DFB laser (hereafter denoted as device A) with a grating period $\Lambda$ of ~497 nm. Output power greater than 6 mW/f was obtained at 160 K. The device lased in cw mode at heat-sink temperatures up to 175 K and exhibited stable single-longitudinal-mode emission with side-mode suppression ratio greater than 30 dB as shown in the inset of Fig. 11. The laser operating at 175 mA and 175 K lased in a single DFB mode of 3355.8 nm and red shifted with increasing current from heating effects. Fig. 12 shows the lasing wavelengths of device A and device H (grating period $\Lambda$~482 nm, shorter than that in device A) in a wide temperature range near the thresholds. Device A has a relatively large temperature tuning rate of ~0.3-0.6 nm/K from 150 to 175 K due to significant heating with high threshold currents at these temperatures. Device H exhibited DFB modes near 3.24 µm with a temperature tuning rate of ~0.2 nm/K from 80 to 135 K. At certain temperatures with the current above the threshold, two DFB modes could be observed as shown in the inset of Fig. 12 for device H, indicative of strong index coupling with negligible gain/loss modulation. Well-separated DFB and FP modes could appear simultaneously at some temperatures and currents. The wavelength range of the FP modes is governed by the temperature sensitive band-gap (or material gain peak), while the shift of the DFB mode is mainly determined by the less temperature sensitive effective index. The rapid detuning of the DFB modes from the gain peak with temperature limits the tuning range of a DFB laser by varying its temperature.

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**Fig. 11.** Current-voltage-light characteristics of a 50-µm-wide and 1.5-mm-long mesa-stripe DFB laser. The inset shows the lasing spectra with the laser operating at several currents and 175 K.

**Fig. 12.** Lasing wavelengths of device A and device H near the thresholds vs. heat sink temperature. The arrows signify the inter-group hopping of FP modes for device A. The inset is the lasing spectra of device H at 110 K with 22 and 33 mA.
The degeneracy of DFB modes is undesirable and can be removed with loss modulation [25]. With this consideration, sample J241 was processed into 15-μm-wide and 1-mm-long mesa stripes with metal contact covering the top surface of the DFB grating. These lasers operated in cw mode in the temperature range from -80 to -185 K with emission wavelengths from -3.5 to 3.6 μm. Fig. 13 shows the lasing spectra of a DFB laser in the temperature range from 90 to 110 K with a stable single mode emission. The single DFB mode red shifted upon increase in temperature or current. The stop band was not observed and the degeneracy was eliminated by the loss modulation as expected. Fig. 14 summarizes the lasing wavelengths of four devices made from J241 with different grating periods (Λ=522.7, 523.8, 527.3, 530.9 nm), showing wavelength tuning as a function of temperature. DFB modes have a tuning rate of ~0.2 nm/K as governed mainly by temperature-dependent effective index n_{eff}. The wavelength of a DFB mode is essentially determined by the grating period Λ according to λ=2n_{eff}Λ, which is manifested by 4 DFB mode tuning curves with different grating periods in Fig. 14. FP modes were also observed from lasers made from J241. The temperature dependence of a FP mode basically followed the variation of the band-gap (or material gain peak) with temperature and has a tuning rate of ~0.8 nm/K in the temperature range that we have examined.

Fig. 13. Spectra of DFB laser fabricated from sample J241 at several current settings and at 90, 100, 110 K.

Fig. 14. Wavelength tuning as a function of temperature that illustrates the difference in the tuning rate between a DFB (solid) and a Fabry-Perot (dotted) modes.

### 4. SUMMARY

Significant progress in the development of type-II mid-IR IC lasers has recently been made in terms of low threshold current densities (e.g. ~9 A/cm² at 80 K) and high temperature operation (e.g. 325 K in pulsed and 200 K in cw modes). These accomplishments were achieved even though device fabrication and packaging were in a preliminary stage and still being perfected, and the mesas were relatively wide with large specific thermal resistance. The observed threshold current densities from our IC lasers are already below any previously reported value among mid-IR lasers at a wide temperature range from 80 K up to room temperature. These accomplishments suggest the high likelihood of IC lasers achieving cw operation near room temperature with relatively high output power when advanced device fabrication/packaging techniques such as facet coating, epi-side-down mounting, and narrow-ridge formation are applied in combination with further improvements in device design and MBE-grown material quality. Continuous wave operation of single-mode DFB IC lasers has been demonstrated at temperatures up to 175 K with side-mode suppression ratio over 30 dB in the wavelength region near 3.3 and 3.5 μm, desirable for sensitive detection of some molecules such as CH₄, HCl and H₂CO.
ACKNOWLEDGMENTS

Authors thank J. K. Liu for his initial help in device fabrication, B. Yang and S. Keo for their contributions in device processing, R. E. Muller and P. M. Echternach for e-beam writing of DFB gratings. They are grateful to C. P. Bankston, P. J. Gunthander, S. D. Gunapala, D. L. Jan, E. A. Kolaw, K. M. Kolwad, T. N. Krabach, and C. F. Ruoff for their encouragement and support. The research described in this paper was performed at the Jet Propulsion Laboratory (JPL), California Institute of Technology, and was supported in part by the National Aeronautics and Space Administration (NASA), Advanced Environmental Monitoring and Control Technology Development Program, Enabling Concepts & Technologies Program, and JPL internal Research & Technology Development program.

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