Low threshold interband cascade lasers operating above room temperature

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Abstract

Mid-IR type-II interband cascade lasers were demonstrated in pulsed mode at temperatures up to 325 K and in continuous mode up to 200 K. At 80 K, the threshold current density was 8.9 A/cm^2 and a cw output power of ~140 mW/facet was obtained.

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Type-II interband cascade (IC) lasers [1] that combine the advantages of quantum cascade (QC) lasers [2] and type-II quantum well (QW) interband lasers can, in theory [3,4], operate in continuous wave (cw) mode up to room temperature with high output power. Although significant advances toward such a high performance level have been achieved [5-7], their performance is still far from the theoretical projections and the reported maximum operation temperatures were limited to 300 K and 150 K in pulsed and cw modes, respectively [7]. One issue is that their threshold current densities are still substantially larger than they need to be, resulting in large amount of heat and thus causing problems for operation at high temperatures, particularly in cw mode. Here, we report on significant progress in IC laser performance including low threshold current density, above-room-temperature operation, and high cw operation temperatures up to 200 K.

Based on the same design, two laser samples, labeled J134 and J137, were grown in a solid source molecular beam epitaxy (MBE) system on unintentionally doped p-type GaSb (001) substrate. The IC laser structure is composed of multiple coupled QWs made from Al(In)Sb, InAs, and Ga(In)Sb layers [5-7] and has 15 cascade stages. The total thickness of the laser structure was near 5 μm with InAs/AlSb superlattice cladding layers. Each active region is comprised of asymmetric AlSb/InAs/GaInSb/InAs/AlSb multiple coupled QWs. In contrast to a simple QW active region [6], this coupled QW structure has a relatively large wave-function overlap between two interband transition states, leading to an enhanced optical gain similar to the W-structure [8, 9] and consequently low threshold current.

After growth, the samples were processed into deep-etched mesa-stripe devices with metal contacts on the top n-type layer and the bottom p-type substrate. Laser bars were cleaved to form cavities from ~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. The emission spectra were obtained by focusing the output optical beam onto the entrance slit of a 0.55-m monochrometer. In pulsed mode, current pulses of 1-μs duration and 1 kHz repetition rate were injected into all laser devices at various temperatures.

Lasers made from J134 operated in pulsed at temperatures up to 325 K, the highest reported for III-V mid-IR diode lasers. The lasing spectra of a 150-μm-wide and 0.8-mm-long laser made is shown in Fig. 1 in the wavelength (λ) range from ~3.21 to 3.27 μm, red shifting when the temperature was raised from 260 to 325 K with a rate ($d\lambda/dT$) of ~0.9 nm/K. The rate ($d\lambda/dT$) 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 [10] and type-I QW diode lasers [11]. This is because the Stark effect plays a more significant role with spatially indirect transitions in type-II IC lasers. Current-voltage-light characteristics of another 150-μm-wide and 1-mm-long mesa stripe laser made are plotted in Fig. 2 at a temperature range from 180 to 320 K, showing significant peak output power at all temperatures. Its external differential quantum efficiency (EDQE) exceeded 500% at 180- 220 K and decreased at the higher temperatures. Its threshold current density (Fig. 3) is significantly smaller than the previously reported values for IC lasers at all temperatures [7]. These 150-μm-wide lasers made from J134 also operated in cw mode at heat-sink temperatures up to 165 K (at ~3.14 μm), higher than the previous record (~150 K for a 65-μm-wide laser at ~3.39 μm) for type-II IC lasers [6].

Lasers made from J137 lased in cw mode at higher temperatures due mainly to the reduction in threshold current that comes with narrower mesa-stripes. The Fig. 4 shows cw

current-voltage-light characteristics of a 110-μm-wide and 1-mm-long mesa stripe laser at a heat-sink temperature range from 80 to 170 K. The output power of ~140 mW/f was obtained at 80 K with a threshold current density of ~8.9 A/cm^2, the lowest reported for mid-IR lasers. The power (wall-plug) efficiency was larger than 13% at 80 K and was still higher than 1% at 170 K. This laser lased at temperatures in cw mode up to 175 K at ~3.25 μm and in pulsed mode up to 315 K with its pulsed current-voltage-light characteristics shown in Fig. 5. When the mesa width was reduced to 30-μm, the cw operation temperature was raised to 200 K as shown in Fig. 6. The inset of Fig. 6 shows its high-resolution lasing spectrum near 3.27 μm at 200 K, where the separation between adjacent longitudinal modes is ~15 Å, in good agreement with the calculated value for a 1-mm-long cavity. As shown in Fig. 6, significant output power can be obtained from an IC laser with a relatively small current at temperatures up to 200 K. This result is comparable or slightly better than the previous record (~195 K) for mid-IR III-V diode lasers with facet coatings and epi-layer-side-down mounting [12]. 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. 3.

We note that our reported powers are conservative since only the loss due to the ~90% transmission of the optical cryostat window was assumed without accounting for beam divergence loss. The lasing wavelengths of lasers made from J134 were slightly shorter than the designed value due to a slight decrease in actual layer thickness due to source material cell depletion in the MBE. The lasing wavelengths of lasers made from J137 were in much better agreement with the design since the MBE growth rates were re-calibrated after J134. This may explain why lasers made from J137, even taking into account the longer emission wavelengths, have lower threshold current densities and lower threshold voltage than lasers made from J134 at

low temperatures. This trend is summarized in Fig. 3. The threshold voltage was lower than 7 V for lasers made from J137 at low temperatures and only larger than the minimum voltage (~6 V) required in an ideal case (15 periods multiplied by the photon energy in eV) by ~1 V, indicating an efficient use of applied bias. However, the threshold voltage increased quickly at temperatures above 250 K. This might cause domains of high electric field in the laser structure, which is detrimental to laser performance and will be investigated in the future.

In conclusion, mid-IR type-II IC lasers have been demonstrated at temperatures up to 325 K in pulsed mode and to 200 K in cw mode with a lowest threshold density of 8.9 A/cm^2 at 80 K. Operation of these IC lasers in cw mode in the thermoelectric cooler range (>230 K) should soon be possible with the application of facet coatings, epi-layer-side down mounting, and further reduction of mesa width, all of which will be explored in our future efforts.

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REFERENCES

1. R. Q. Yang, "Infrared laser based on intersubband transitions in quantum wells", Superlattices and Microstructures, vol. 17, No. 1, pp. 77-83, 1995.
2. J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, "Quantum Cascade Lasers", *Science* **264**, 553-556, April 1994.
3. J. R. Meyer, I. Vurgaftman, R. Q. Yang, and L. R. Ram-Mohan, "Type-II and type-I interband cascade lasers", Electronics Letters, **32**, pp. 45-46, Jan. 1996.
4. I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, "High-power/low-threshold type-II interband cascade mid-IR laser–Design and modeling", IEEE Photo. Tech. Lett. **9**, pp. 170-172, Feb 1997.
5. R. Q. Yang, "Mid-Infrared Interband Cascade Lasers Based on Type-II Heterostructures", *Microelectronics J.* **30**, 1043-1056 (1999); and references therein.
6. R. Q. Yang, J. D. Bruno, J. L. Bradshaw, J. T. Pham, D. E. Wortman, Physica E **7**, 69 (2000).
7. R. Q. Yang, J. L. Bradshaw, J. D. Bruno, J. T. Pham, D. E. Wortman, "Mid-IR type-II interband cascade lasers", IEEE J. Quantum Electron. 38, 559 (2002); and references therein.
8. J. R. Meyer, C. A. Hoffman, F. J. Bartoli, and L. R. Ram-Mohan, "Type-II quantum-well lasers for the mid-wavelength infrared", Appl. Phys. Lett. **67**, 757-759, 1995.
9. C. L. Felix, W. W. Bewley, I. Vurgaftman, J. R. Meyer, D. Zhang, C.-H. Lin, R. Q. Yang, and S. S. Pei, "Interband Cascade Laser Emitting > 1 Photon per Injected Electron", IEEE Photonics Technol. Lett. **9**, 1433-1435, Nov. 1997.
10. W. W. Bewley, C. L. Felix, E. H. Aifer, D. W. Stokes, I. Vurgaftman, L. J. Olafsen, J. R. Meyer, M. J. Yang, and H. Lee, "Thermal characterization of diamond-pressure-bond heat

sinking for optically pumped mid-infrared lasers", IEEE Quantum Electron. Vol. 35, pp. 1597-1599, Nov. 1999.

11. H. K. Choi and G. W. Turner, "Antimonide-based mid-infrared lasers", chapter 7 in *Long Wavelength Infrared Emitters Based on Quantum Wells and Superlattices*, edited by M. Helm (Gordon and Breach, Singapore, 2000), pp. 225-305.

12. W. W. Bewley, H. Lee, I. Vurgaftman, R. J. Menna, C. L. Felix, R. U. Martinelli, D. W. Stokes, D. Z. Garbuzov, J. R. Meyer, M. Maiorov, J. C. Connolly, A. R. Sugg, G. H. Olsen, "Continous-wave operation of λ=3.25 μm broadened-waveguide W quantum well diode lasers up to T=195K", *Appl. Phys. Lett.* **76**, pp. 256-258, Jan. 2000.

Figure Captions

Fig. 1. Lasing spectra from a 150-μm-wide and 0.8-mm-long mesa-stripe laser in pulsed mode and at several temperatures.

Fig. 2. Current-voltage-light (*I*-V-*L*) characteristics of a 150-μm-wide and 1-mm-long mesa-stripe laser in pulsed mode at several temperatures.

Fig. 3. Threshold current density and threshold voltage vs the heat-sink temperature for lasers made from J134 and J137. Triangles are for 0.8-mm-long lasers and the others are for 1-mm-long lasers. The inset is the lasing spectra for a 30-μm-wide laser made from J137 at 310 K.

Fig. 4. Current-voltage-light (*I*-V-*L*) characteristics and power efficiency of a 110-μm-wide and 1-mm-long mesa-stripe laser made from J137 in cw mode at several temperatures.

Fig. 5. Current-voltage-light (*I*-V-*L*) characteristics of a 110-μm-wide and 1-mm-long mesa-stripe laser in pulsed mode at several temperatures.

Fig. 6. Current-voltage-light (*I*-V-*L*) characteristics of a 30-μm-wide and 1-mm-long mesa-stripe laser in cw mode at several temperatures and its high-resolution lasing spectrum (inset) at 200 K.

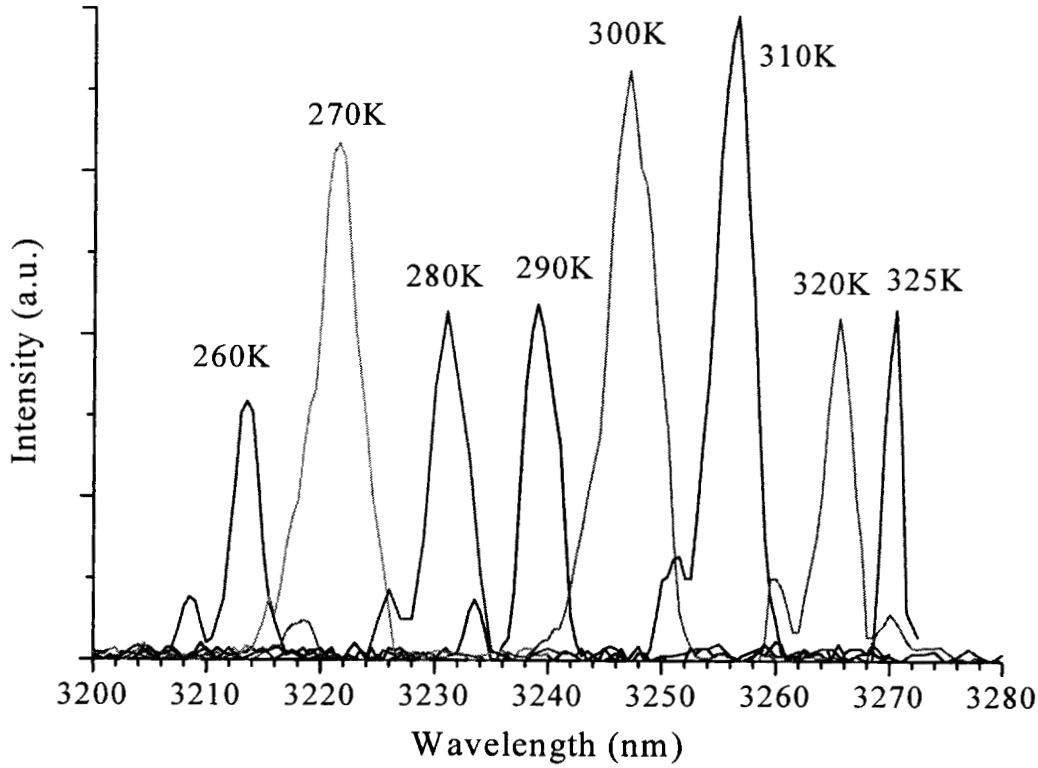
300K
310K
270K
280K
290K
320K
325K
260K
Intensity (a.u.)
3200
3210
3220
3230
3240
3250
3260
3270
3280
Wavelength (nm)

Fig. 1

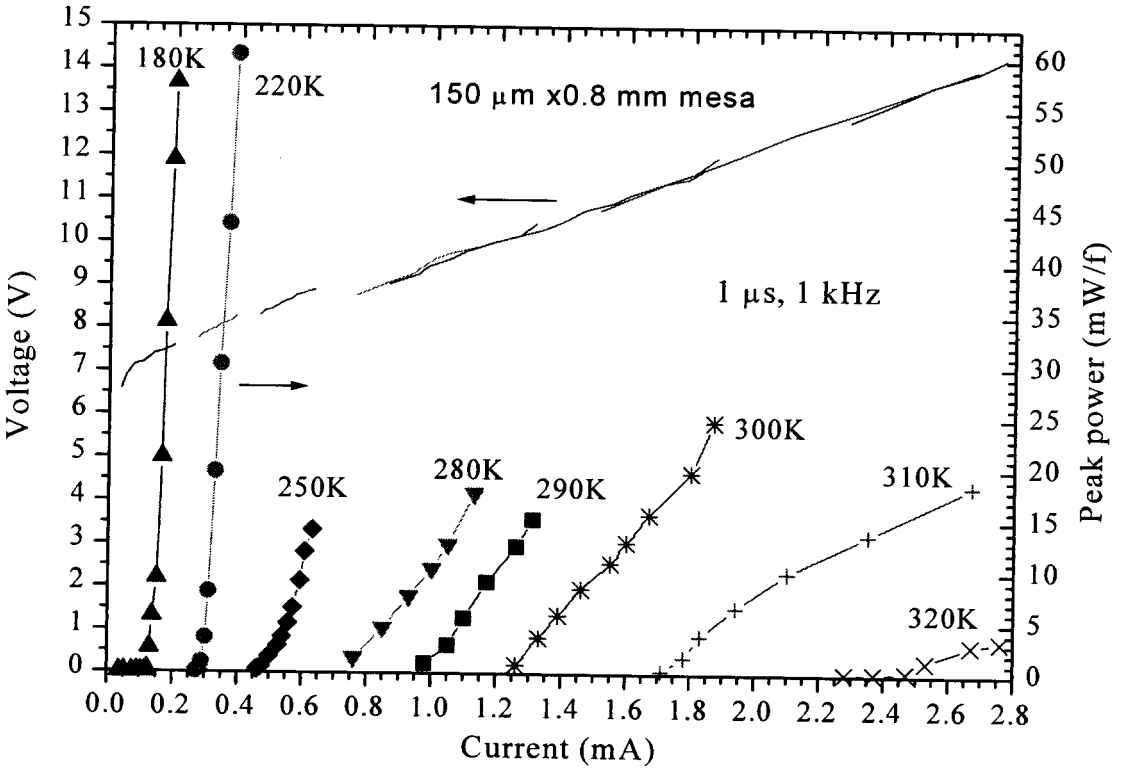
150 μm x0.8 mm mesa
1 μs, 1 kHz
180K
220K
250K
280K
290K
300K
310K
320K
Voltage (V)
Peak power (mW/f)
Current (mA)

Fig. 2

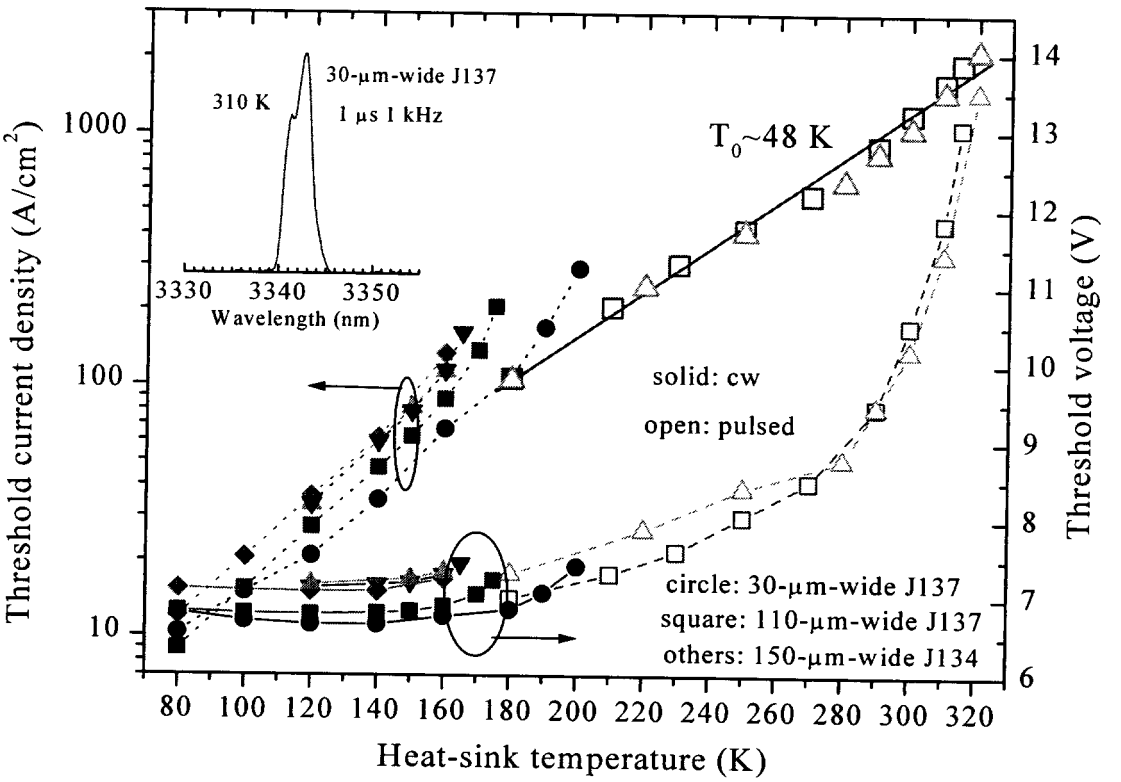
Threshold current density (A/cm^2)
1000
100
10
Threshold voltage (V)
14
13
12
11
10
9
8
7
6
80 100 120 140 160 180 200 220 240 260 280 300 320
Heat-sink temperature (K)
310 K
30-μm-wide J137
1 μs 1 kHz
3330 3340 3350
Wavelength (nm)
T_0~48 K
solid: cw
open: pulsed
circle: 30-μm-wide J137
square: 110-μm-wide J137
others: 150-μm-wide J134

Fig. 3

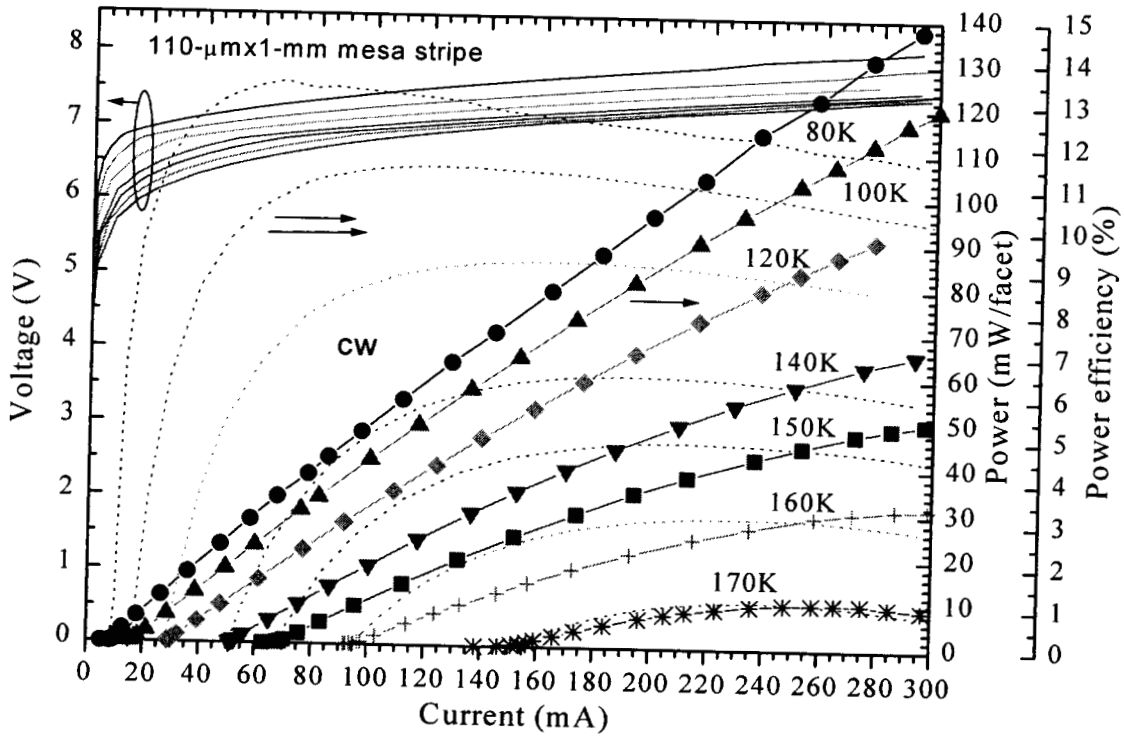
110-μmx1-mm mesa stripe
CW
80K
100K
120K
140K
150K
160K
170K
Voltage (V)
Current (mA)
Power (mW/facet)
Power efficiency (%)

Fig. 4

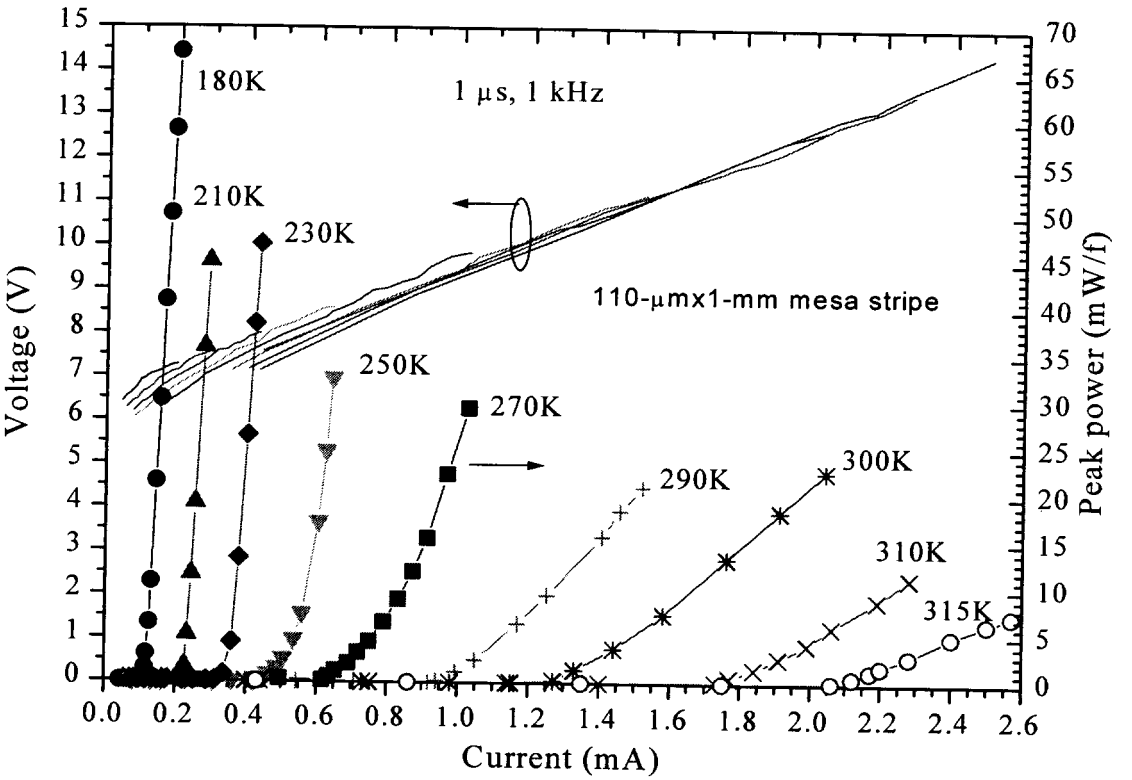
180K
210K
230K
250K
270K
290K
300K
310K
315K
1 μs, 1 kHz
110-μmx1-mm mesa stripe
Voltage (V)
Peak power (mW/f)
Current (mA)

Fig. 5

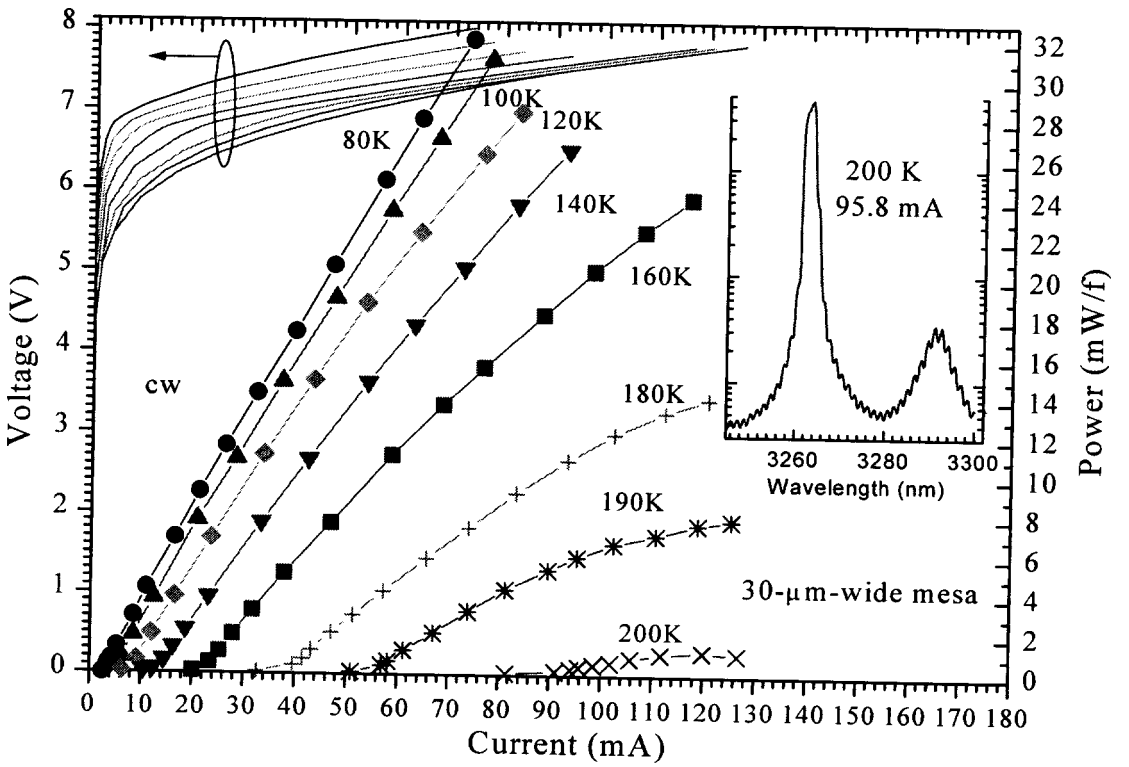
Voltage (V)
Power (mW/f)
Current (mA)
cw
80K
100K
120K
140K
160K
180K
190K
200K
30-μm-wide mesa
200 K
95.8 mA
Wavelength (nm)
3260
3280
3300

Fig. 6