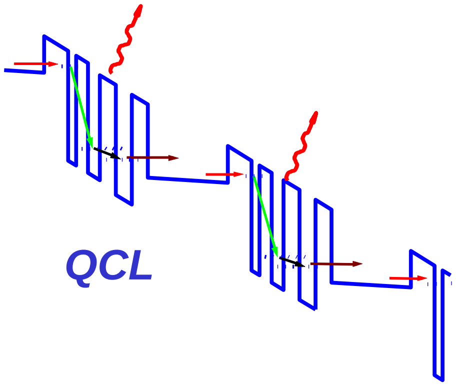
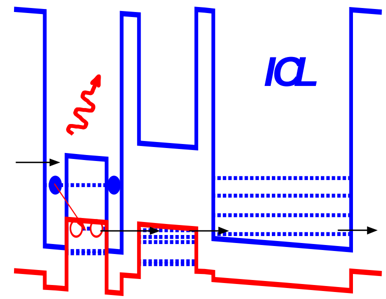
PERFORMANCE TRADE-OFFS: INTERSUBBAND vs. INTERBAND QUANTUM CASCADE LASERS





International Workshop on Quantum Cascade Lasers
(Sevilla, 5 January 2004)

J. R. Meyer, I. Vurgaftman, & W. W. Bewley *(Naval Research Laboratory)*

With devices from: Manijeh Razeghi & Steve Slivken *(Northwestern U.)*

Embedded Talk: ***PROGRESS & CHALLENGES IN THE DEVELOPMENT OF INTERBAND CASCADE LASERS***
R. Q. Yang & C. J. Hill ***(JPL)***

Question: **Which most promising for high cw powers in mid-IR (3-5 μm)?**

Report Documentation Page

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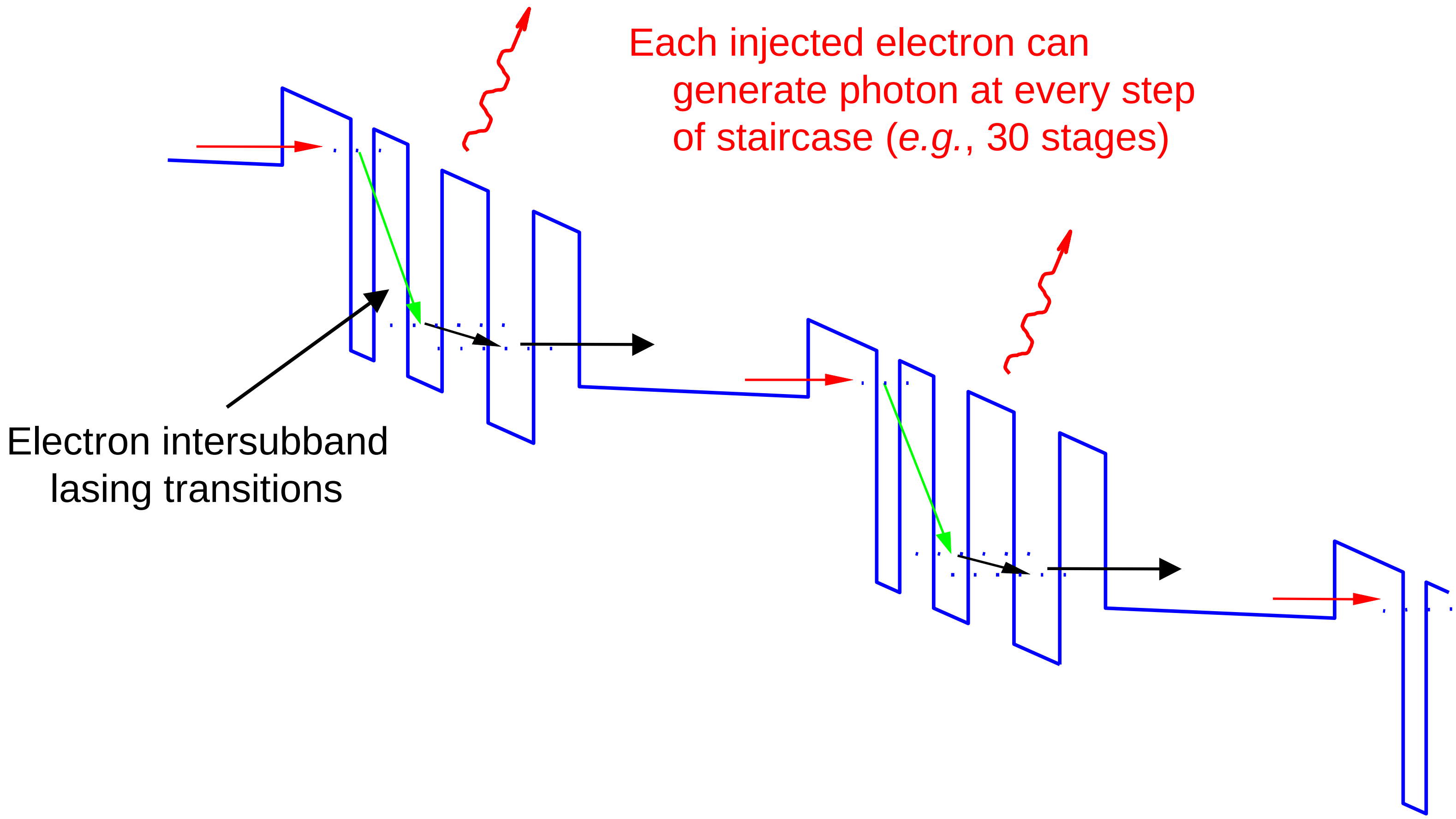
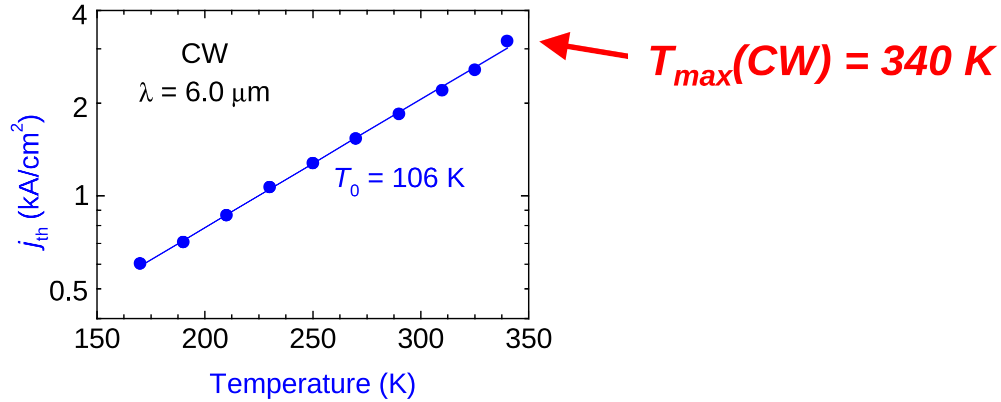
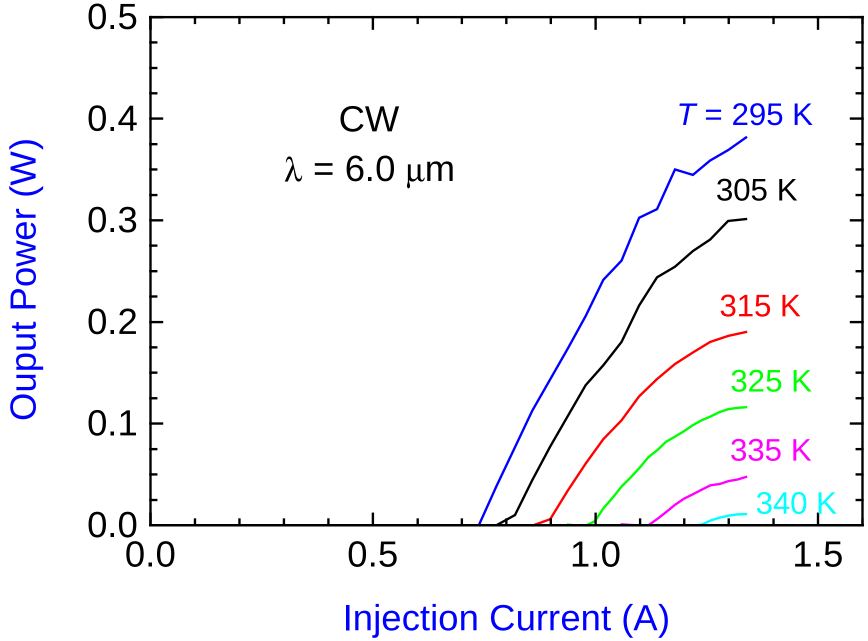
QUANTUM CASCADE LASER (QCL)

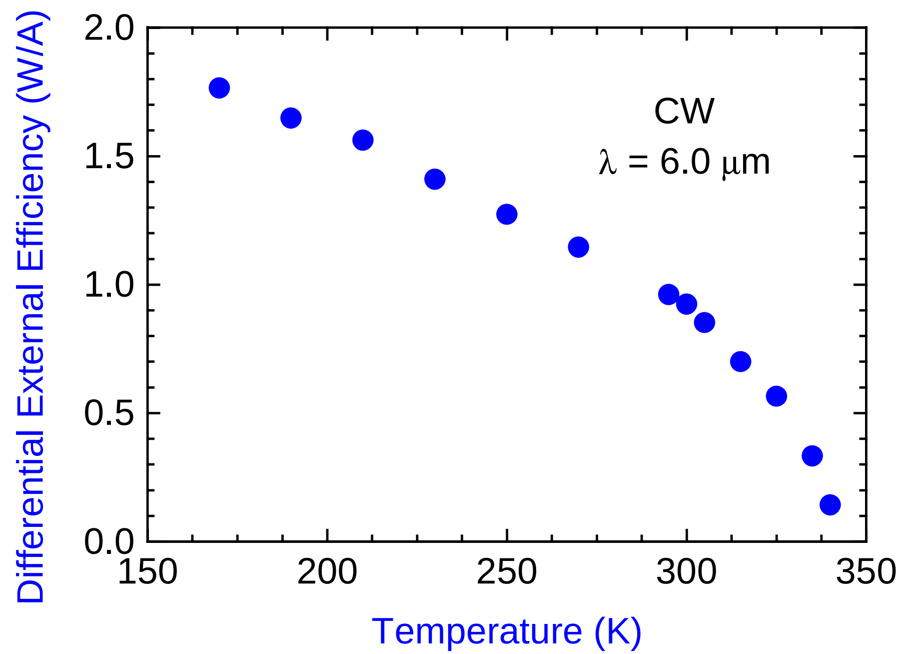


- *Advantages:* Multiple stages for high slope efficiency, Small threshold carrier density, Large T_0, Mature materials (InP/GaAs), Low LEF
- *Disadvantages:* Multiple stages require greater heat dissipation, Short phonon lifetime increases threshold, Strain compensation required to reach $\lambda < 5\ \mu m$

NRL CHARACTERIZATION OF NORTHWESTERN QCLs *(Devices courtesy of M. Razeghi & S. Slivken)*

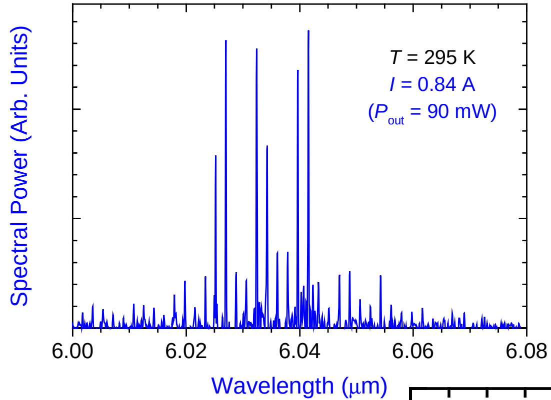


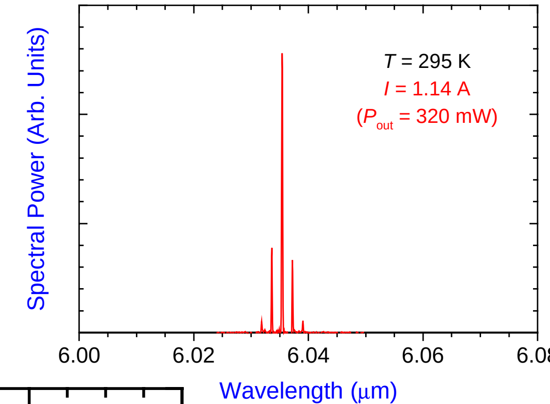


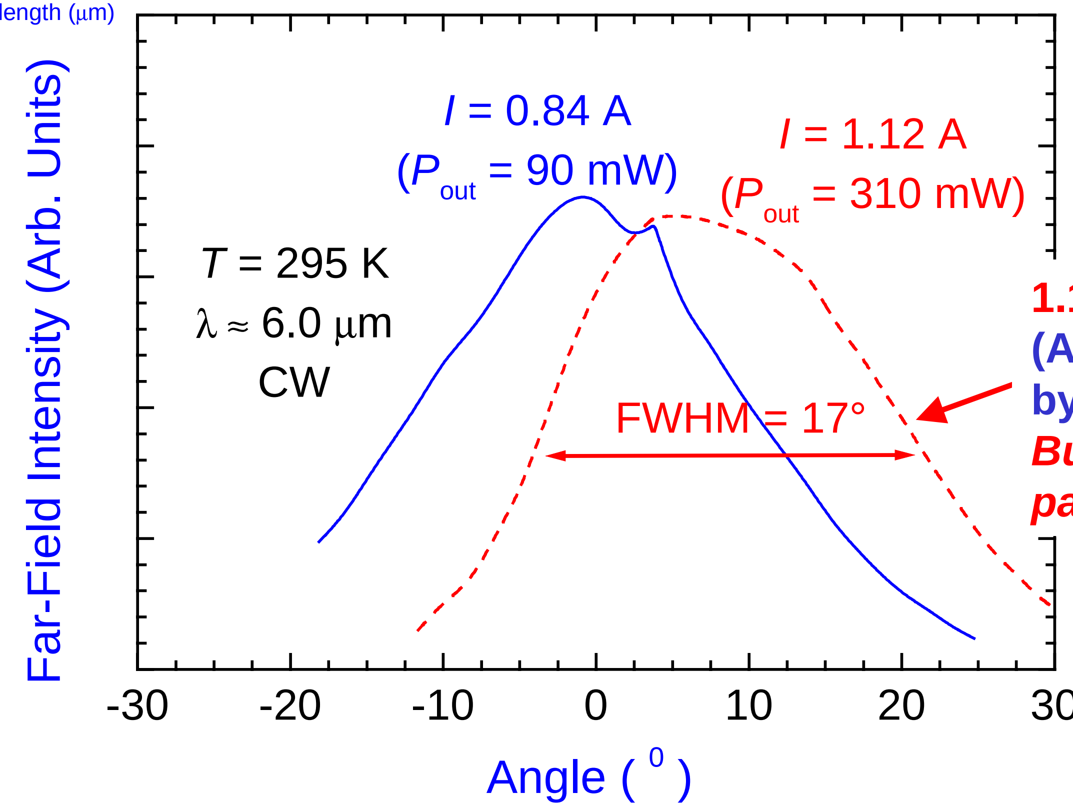


CW P_{out} = 360 mW @ 300 K, 110 mW @ 325 K, η_{wall} = 2.7% @ 300 K

SPECTRA & FAR-FIELD

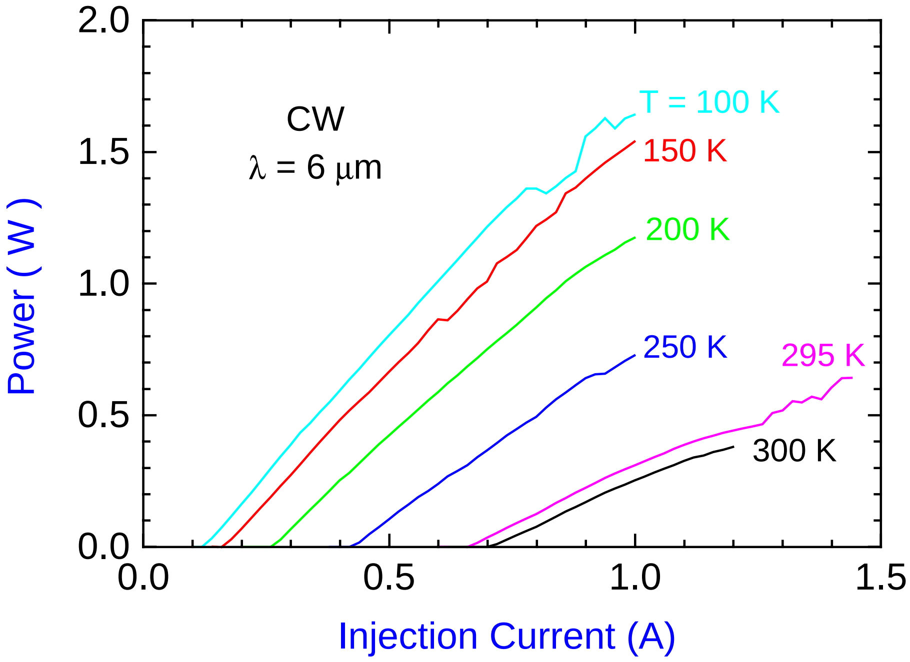


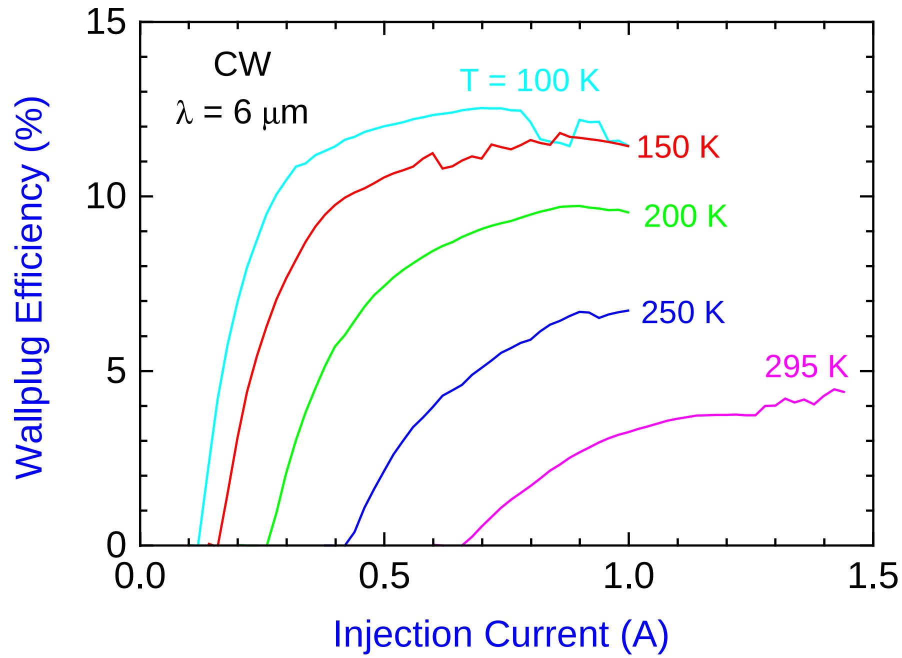




1.14 × Diffraction Limit
(Assumes index guiding by 13-µm mesa)
But tilt implies at least partial gain-guiding

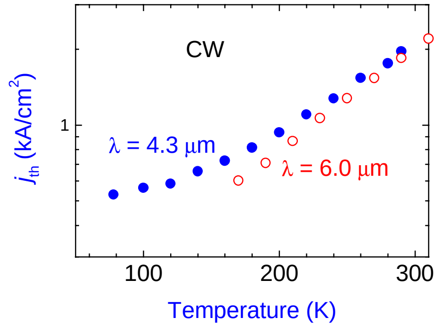
NEW 6 μm LASER

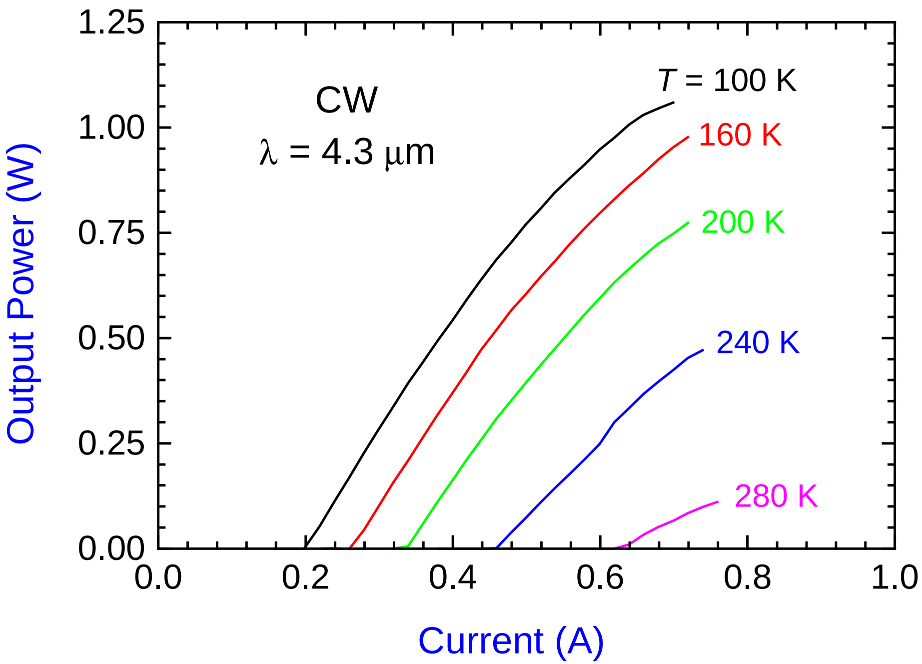


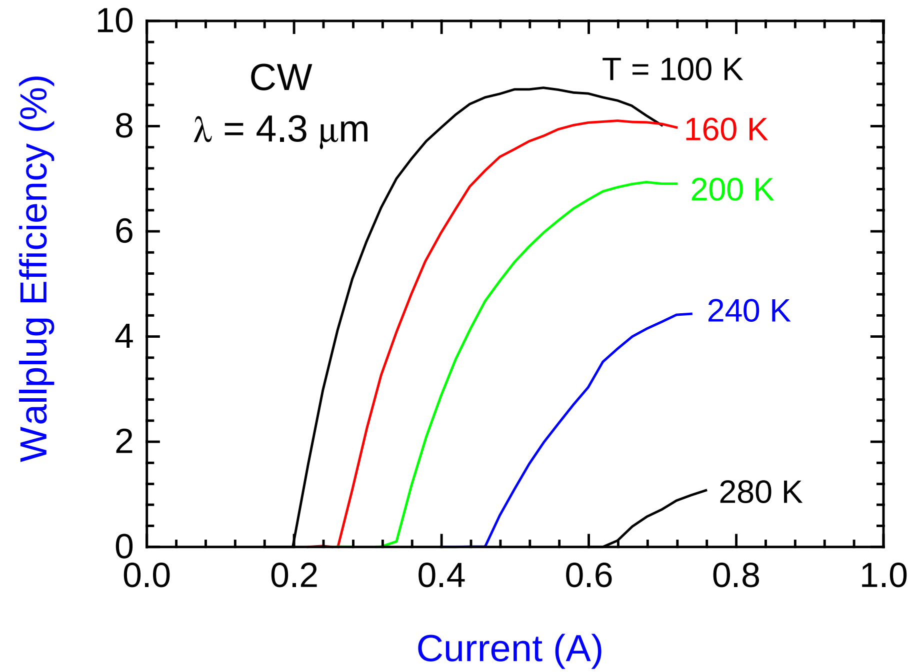


CW P_{out} > 1.1 W @ 200 K, 640 mW @ 295 K, η_{wall}(295K) = 4.5%

SHORTEN WAVELENGTH TO 4.3 μm



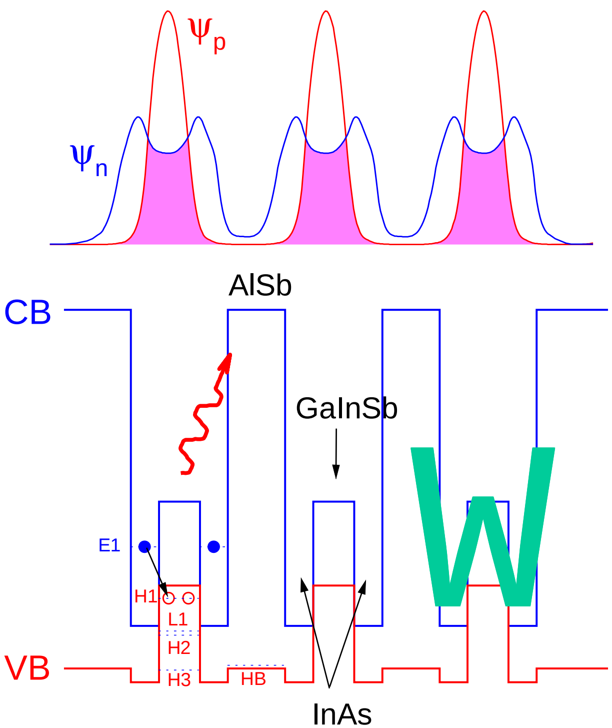




CW @ 160 K: $P_{out} \approx 1$ W, η_{wall} = 8.1%

TYPE-II ANTIMONIDE "W" LASER

Meyer et al. APL 67, 757 (1995);
U.S. Patent # 5,793,787



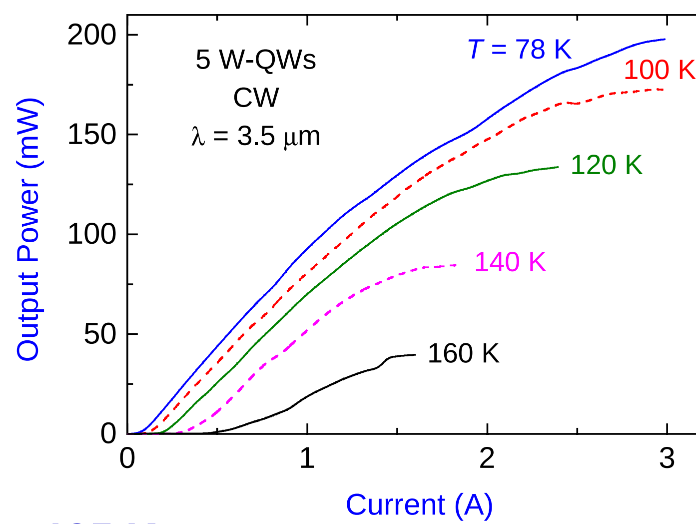
Advantages:

- *Vs. type-I diodes:* High differential gain, excellent electrical confinement, Auger suppression
- *Vs. QCL:* Interband relaxation for lower j_{th}, Single stage for lower heat-dissipation threshold

Disadvantages:

- Lower slope efficiency, Immature GaSb-based materials, *Far less optimized*

MBE at Sarnoff



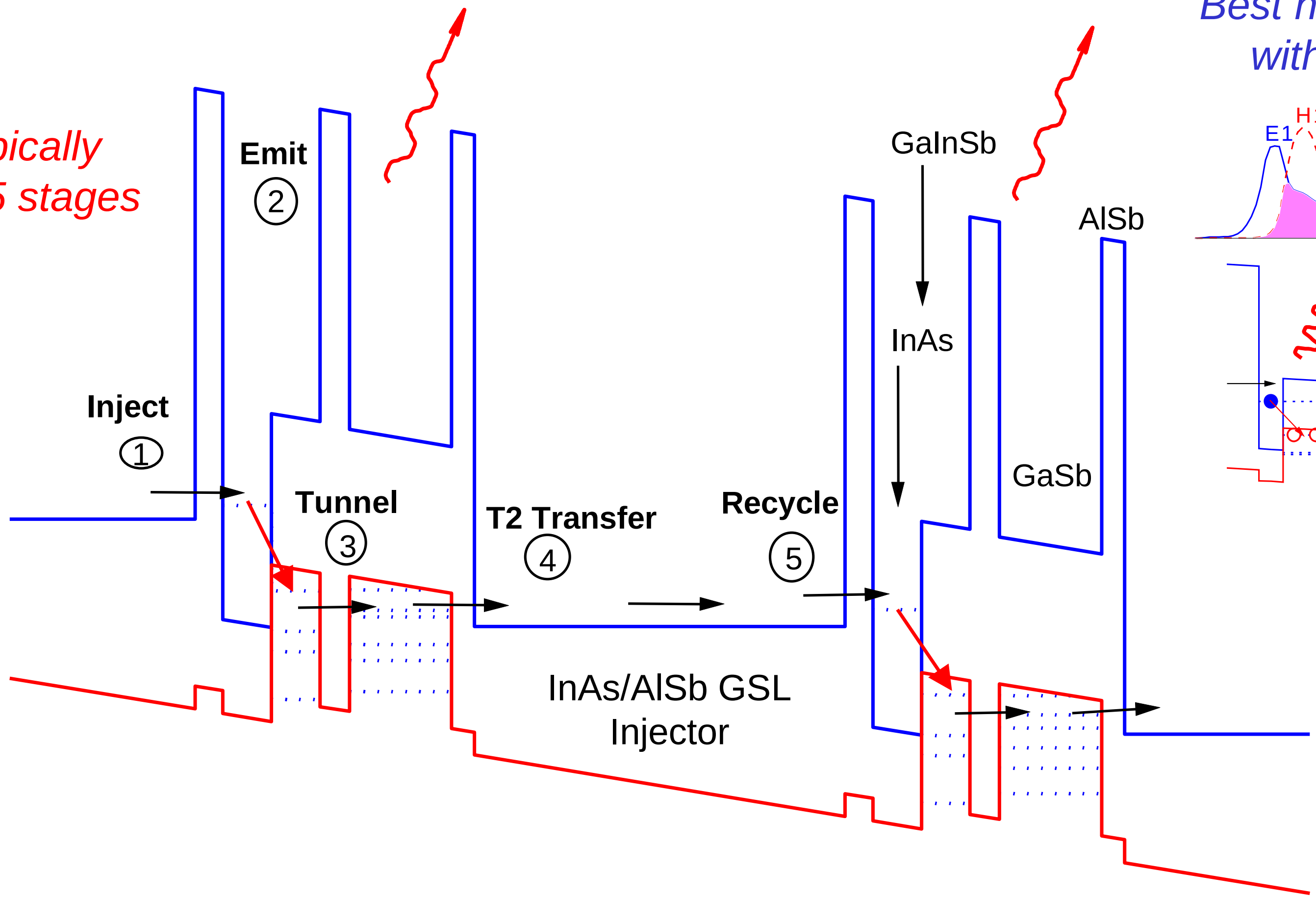
cw T_{max} = 195 K

η_{wall} = 7.2% @ 78 K, 5.4% @ 140 K

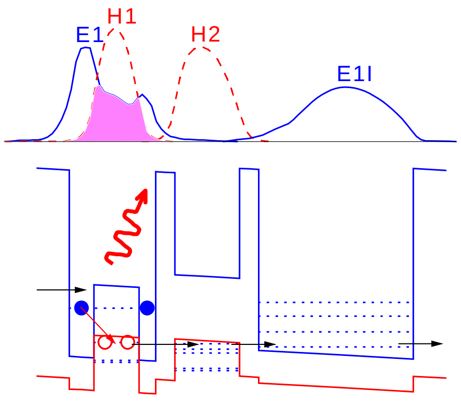
INTERBAND CASCADE LASER (ICL)

First proposed: *R. Q. Yang, Superlatt. Microstruct. 17, 77 (1995)*

Typically 15-25 stages



Best high-T results with W active



W-ICL

Advantages: High slope efficiency (Multiple stages), Lower threshold (long τ_R)

Disadvantages: Higher heat-dissipation threshold (Multiple stages), GaSb-based

Progress and Challenges in the Development of Interband Cascade Lasers

Rui Q. Yang and Cory J. Hill

Jet Propulsion Laboratory
California Institute of Technology, Pasadena, CA

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NASA Advanced Environmental Monitoring and Control Program

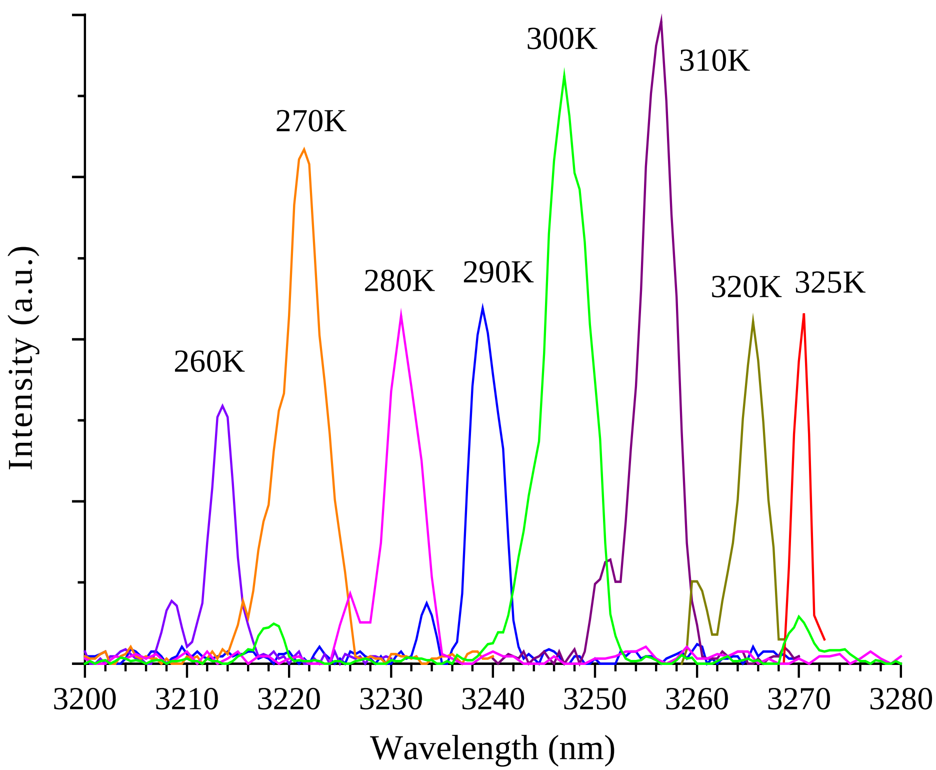
NASA Enabling Concepts and Technologies Program

JPL Internal Research and Technology Development Program

International Workshop on Quantum Cascade Lasers
Seville, Spain, Jan. 4-8, 2004

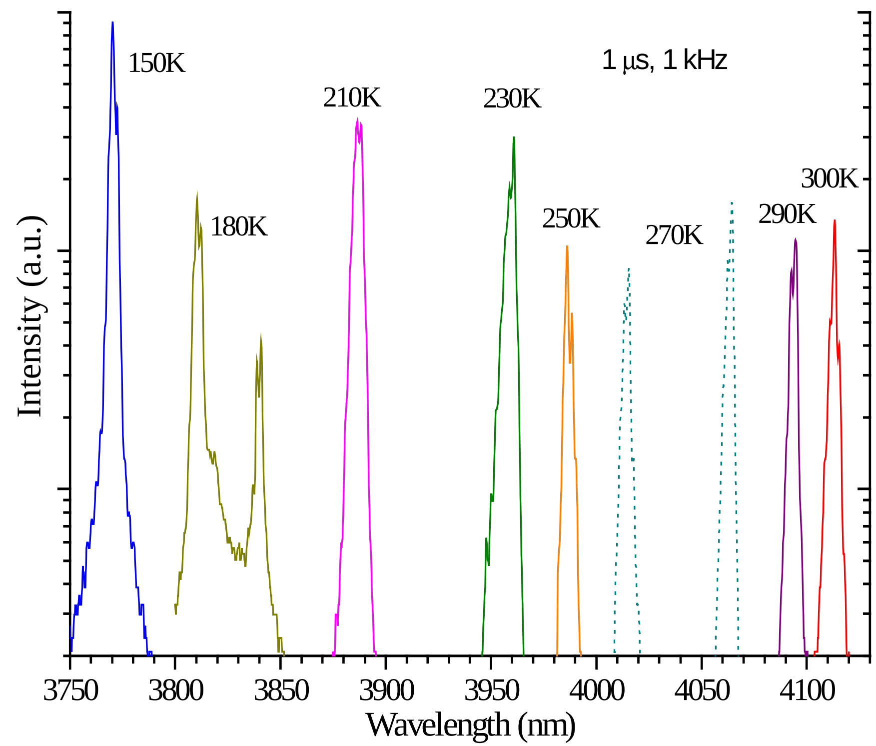
HIGHER-TEMPERATURE OPERATION

15 stages, 150 μm x 0.8 mm mesa



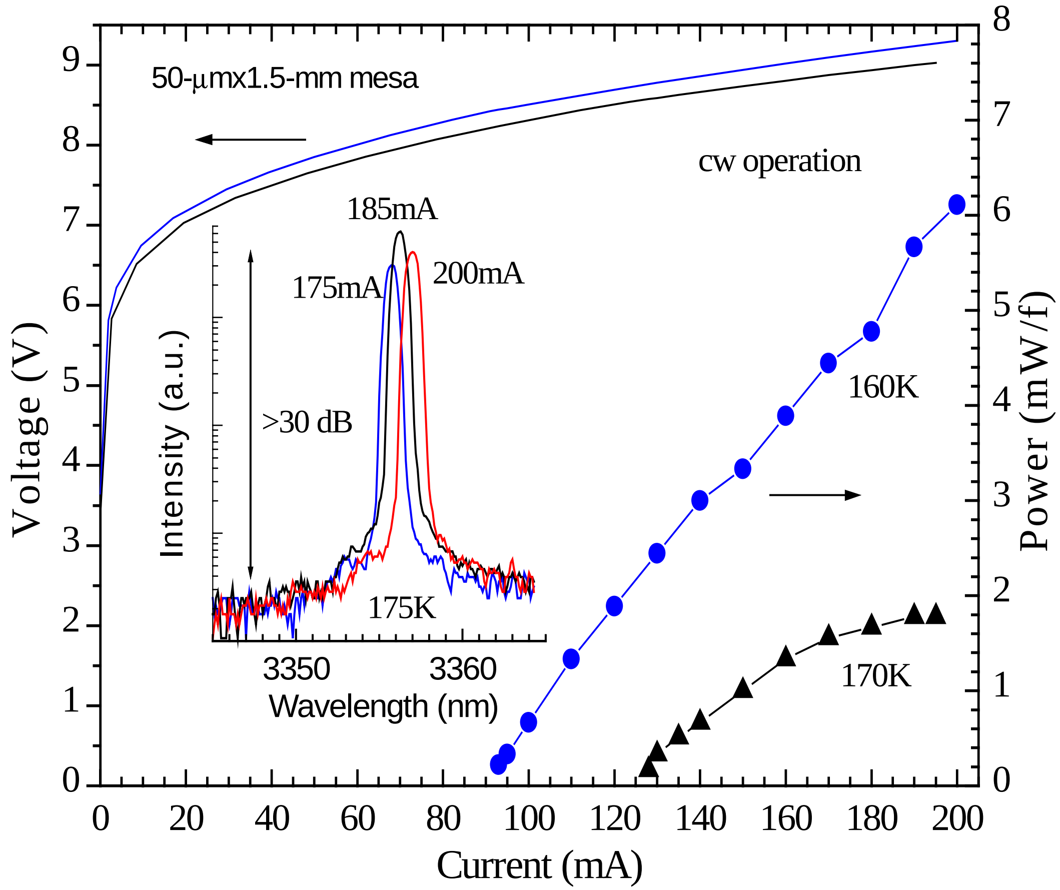
Pulsed lasing at λ = 3.27 μm up to 325 K (Limited by circuit ringing & temperature setting of cryostat)

23-stages, 150-μm x 1-mm mesa



Longest-wavelength III-V interband diode laser operating at room temperature (λ = 4.1 μm)

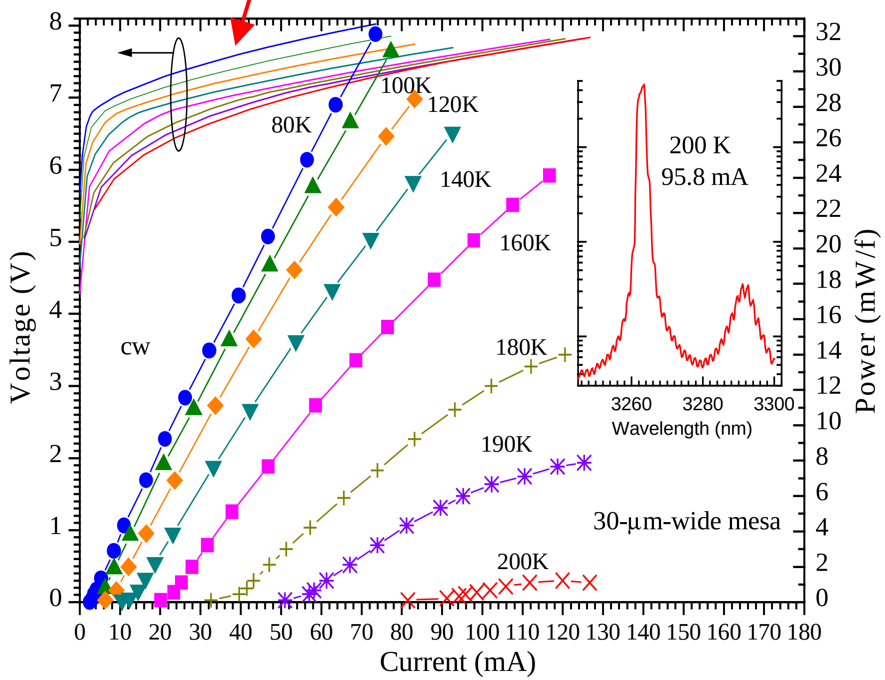
DFB IC LASERS

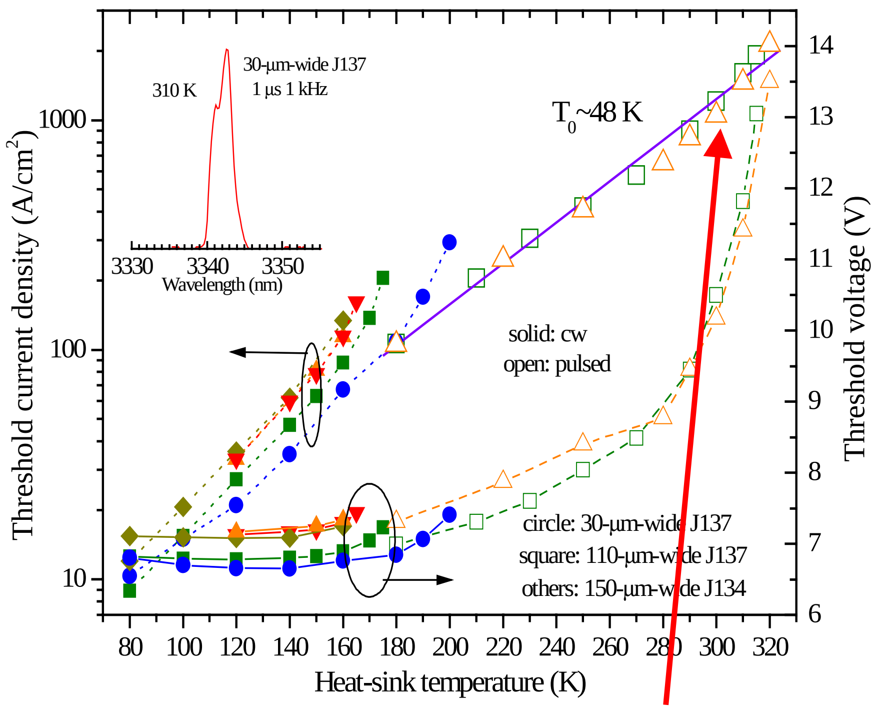


- DFB lasers operated cw up to 175 K in single mode (> 30 dB sidemode suppression)
- Wavelength tunable with current at a rate of ~0.05 nm/mA
- Temperature tuning coefficient ~0.2 nm/K
- Output power (>1 mW) at 175 K enough for gas sensing

LOW THRESHOLD, HIGH CW T_{max}

Excellent voltage efficiency ($\eta\omega$ > 0.9eV$_{th}$)





j_{th}(300K) = 1.05 kA/cm²
(Lower than any QCL)

J_{th} (200K in cw) ~304 A/cm² (30-µm-wide device)
R_{sth} ~ 14 K·cm²/kW (specific thermal resistance)

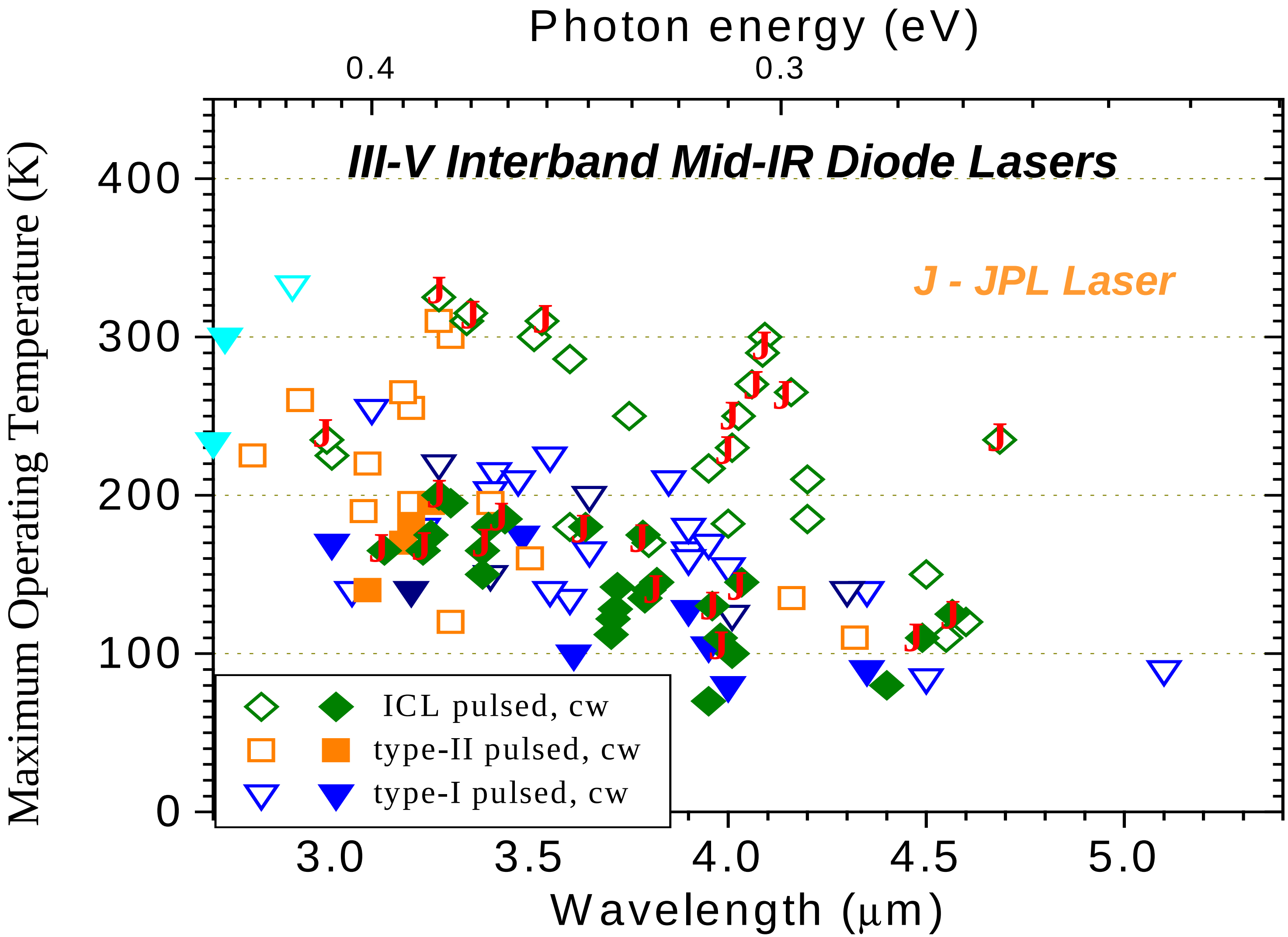
If R_{sth} reduced to 2 K·cm²/kW (smaller device size & better package):
theoretical cw T_{max} ≥ 285 K

Related Maxion results:

At 80 K: η_{wall} = 23%, DEQE ≈ 1 W/A (532%) ***cw T_{max} = 214 K***

JPL ICL STATUS: T_{max}

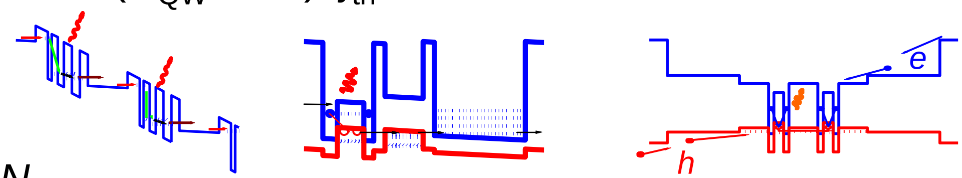
(Compared to literature data, as of 9/2003)



HEAT DISSIPATION REQUIREMENTS AT 300 K
(QCL vs. W-ICL vs. W-Diode)

Current best:

- *QCL:* Current best cw threshold is $j_{th} \approx 1.9$ kA/cm^2 (pulsed 1.2 kA/cm^2 reported), bias (N = 30 stages) is $V_{th} \approx 9$ V – Means $I_{dis} \approx 17$ kW/cm^2 must be dissipated
- *ICL:* Best reported pulsed is $j_{th} \approx 1.05$ kA/cm^2 at $V_{th} = 10.2$ V (N = 15) – Means $I_{dis} \approx 11$ kW/cm^2
- *W-Diode:* For only pulsed 300 K result to date ($N_{QW} = 10$), $j_{th} \approx 16$ kA/cm^2 at $V_{th} \approx$ 1.2 V – Means $I_{dis} \approx 19$ kW/cm^2



Scaling:

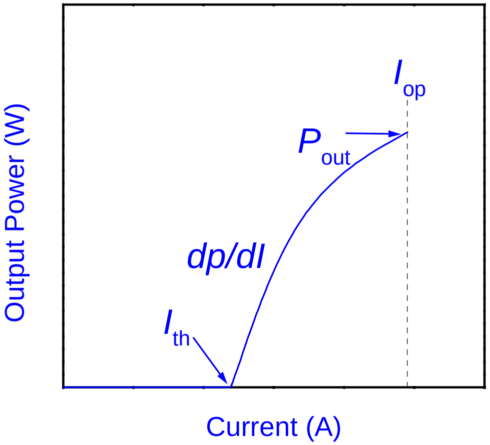
- *QCL:* j_{th} scales with loss; V_{th} scales with N
- *ICL:* j_{th} scales with Auger lifetime (τ_A), depends on loss; V_{th} scales with N
- *W-Diode:* j_{th} scales with N_{QW} & τ_A, depends on loss; Single-stage $V_{th} \approx \eta\omega$

Headroom:

- *QCL:* How much further decrease of loss?; Decrease N to decrease V_{th}? (So far, j_{th} then increases) [$I_{dis} \approx 8\text{-}10$ kW/cm^2 probable – More?]
- *ICL (15-25 stages):* Much less mature so probably more headroom – Optimize V_{th} & possibly τ_A [$I_{dis} \approx 5\text{-}6$ kW/cm^2 probable – More?]
- *W-Diode:* Very immature, so considerable headroom; $V_{th} \approx 0.5$ V; Loss optimization may allow N_{QW} = 3-5 [$I_{dis} \approx 5$ kW/cm^2 probable – More?]
- *Hybrid W-ICL with 3-5 stages (only enough to overcome loss):* Combines higher gain of ICL with lower V_{th} ($\approx$ 1.5-2.5 V) of W-Diode [Expect $I_{dis} < 3$ kW/cm^2]

HIGH POWER: WHAT ABOUT ABOVE j_{th}?

High-power laser must reach & exceed threshold, maintain large slope, minimize droop



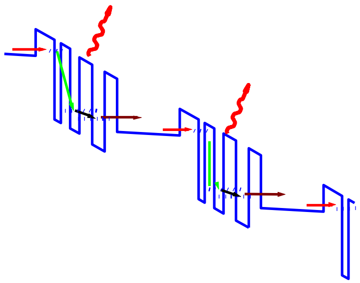
- *Heat sinking:* InP overgrowth favors QCL, but gold plating may neutralize (Maxion ICL reports lowest R_{sp})
- *Higher T_0 of QCL:* Slower performance degradation for given ΔT
- Slope efficiency depends on loss & number of stages (N)
  - *Loss:* Thus far, lower in QCL (≈ 10 cm^{-1} *vs.* ≥ 20 cm^{-1})
    - Advantage likely to persist because: (1) Fewer carriers, (2) No holes
  - *Slope efficiency:* Thus far, higher in QCL (*e.g.*, 1 W/A for NU QCL @ 300 K *vs.* 0.42 W/A for Maxion ICL @ 200 K) – Immature ICL will improve
- *Broaden stripe:* Probably a necessity when scaling power up to ≥ 10 W range
  - Precludes lateral heat flow, so low I_{dis} even more critical
  - Broad-stripe QCL (lower LEF) should maintain better beam quality
  - Photonic-Crystal DFB approach may improve both QCLs & ICLs

OTHER CONSIDERATIONS

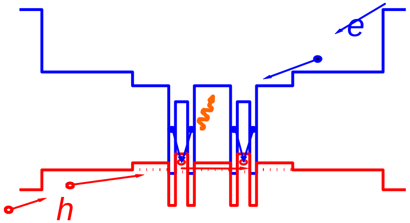
- *Manufacturability:* InP-based materials growth/processing (QCLs) far more mature than GaSb-based (ICLs)
- *Wavelength coverage (Apples to oranges?):* Above analysis compares QCLs emitting at $\lambda \approx 6$ μm to ICLs emitting at $\lambda \approx 3.5$ μm
  - Both get worse as they move toward the middle – Advantages will shift!
  - *One likely outcome:* QCLs will be advantageous at $\lambda > \lambda_{\text{Cross}}$ while ICLs advantageous at $\lambda < \lambda_{\text{Cross}}$ – Value of λ_{Cross} remains to be determined
- *Advantage also shifts with temperature:* Scenarios where QCLs are favored at $T \geq 300$ K may shift to ICLs with TE-cooling (*e.g.*, 240 K)
  - *ICL in low-T limit:* $j_{\text{th}} = 9$ A/cm^2

CONCLUSIONS

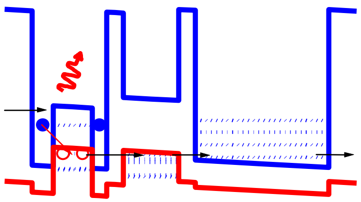
- Dramatic recent progress by both QCLs & ICLs
- High-power 3-5 μm CW lasing with electrical pumping at ambient (or TE-cooler) temperature seems increasingly likely
- ICL (or especially “hybrid” ICL) projected to require less power dissipation, but QCL has other advantages
- Jury still out on which will ultimately dominate under given λ & T constraints (Where is λ_{Cross}?)_



QCL



W-Diode



W-ICL