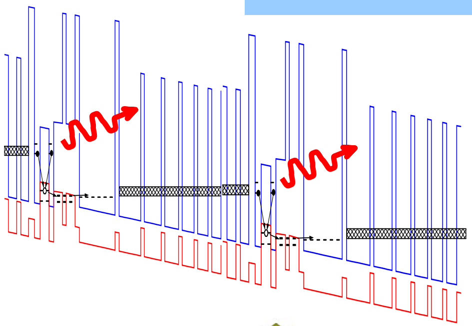
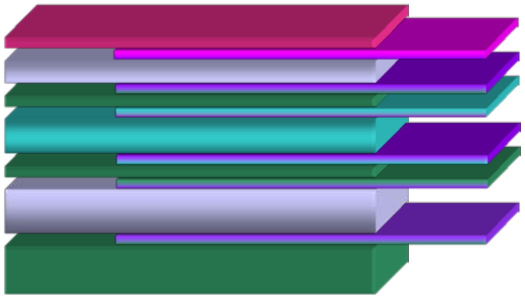
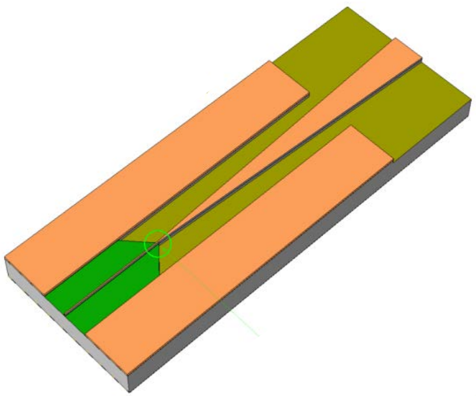
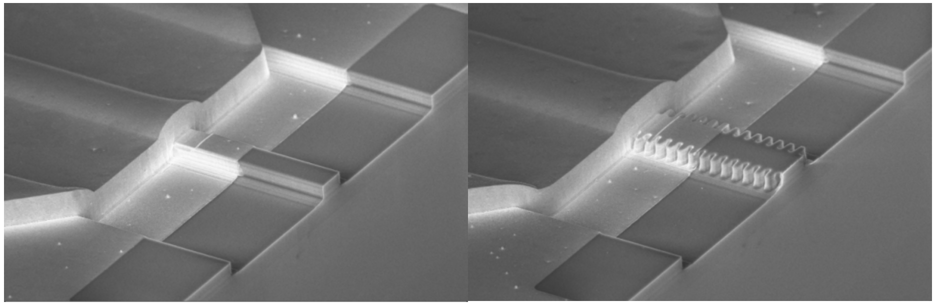
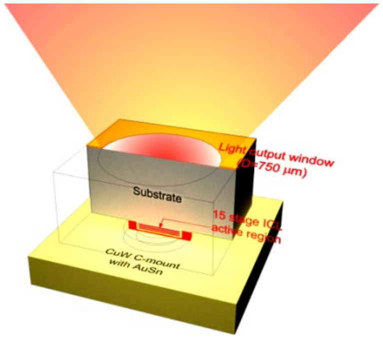
HIGH-BRIGHTNESS INTERBAND CASCADE LASERS











Conference on Lasers and Electro-Optics – San Jose CA (12 May 2015)

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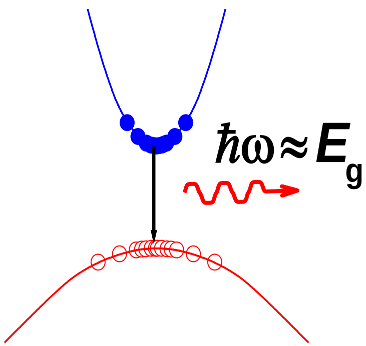
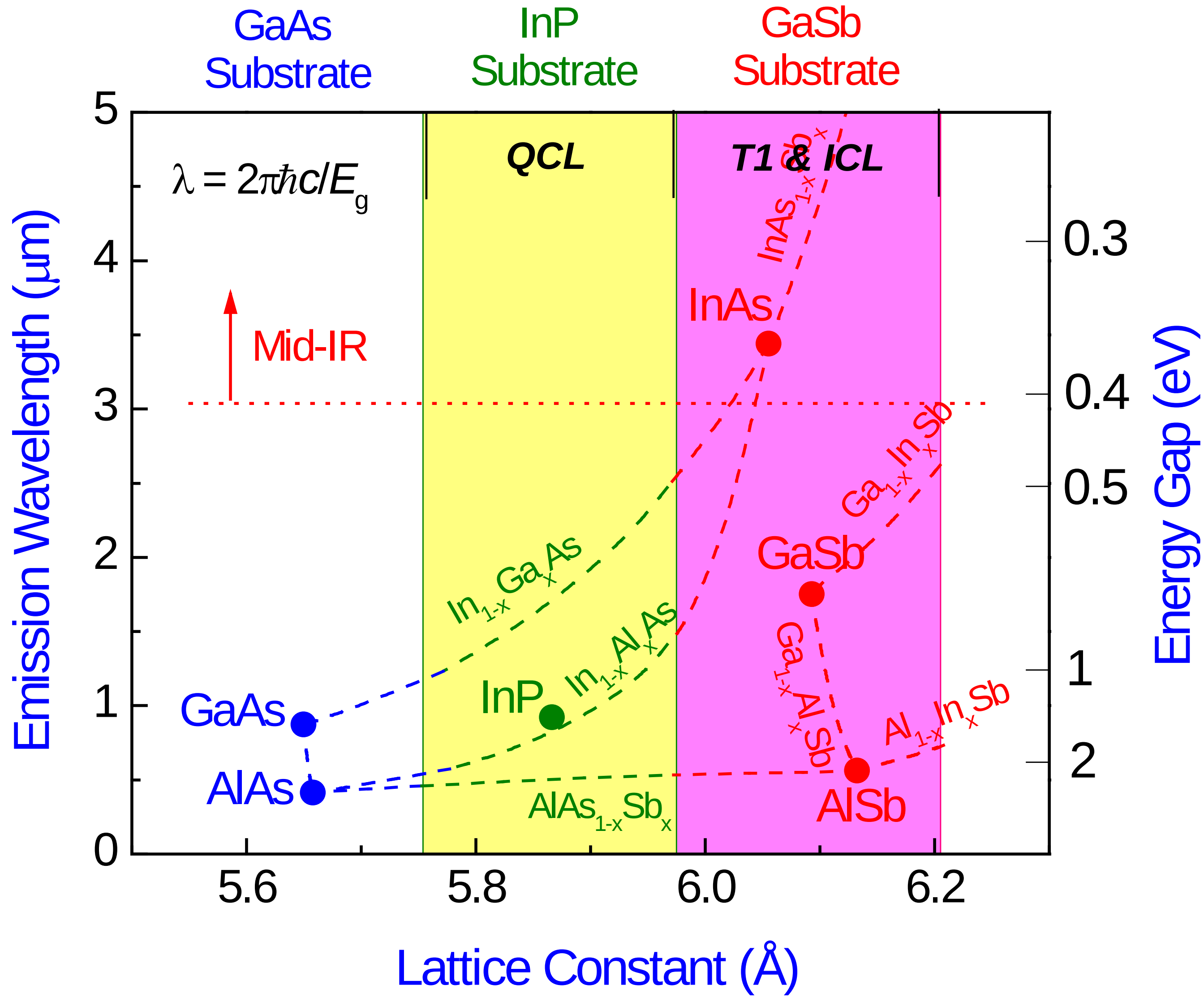
III-V SEMICONDUCTOR LASER FAMILIES





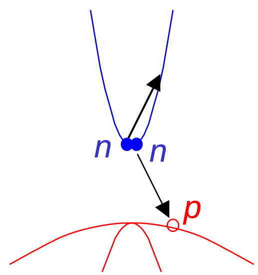
***Interband mid-IR requires GaSb-Based:* Great flexibility, but other issues…**

WHY IS LASING @ LONG λ SO #%$ DIFFICULT?

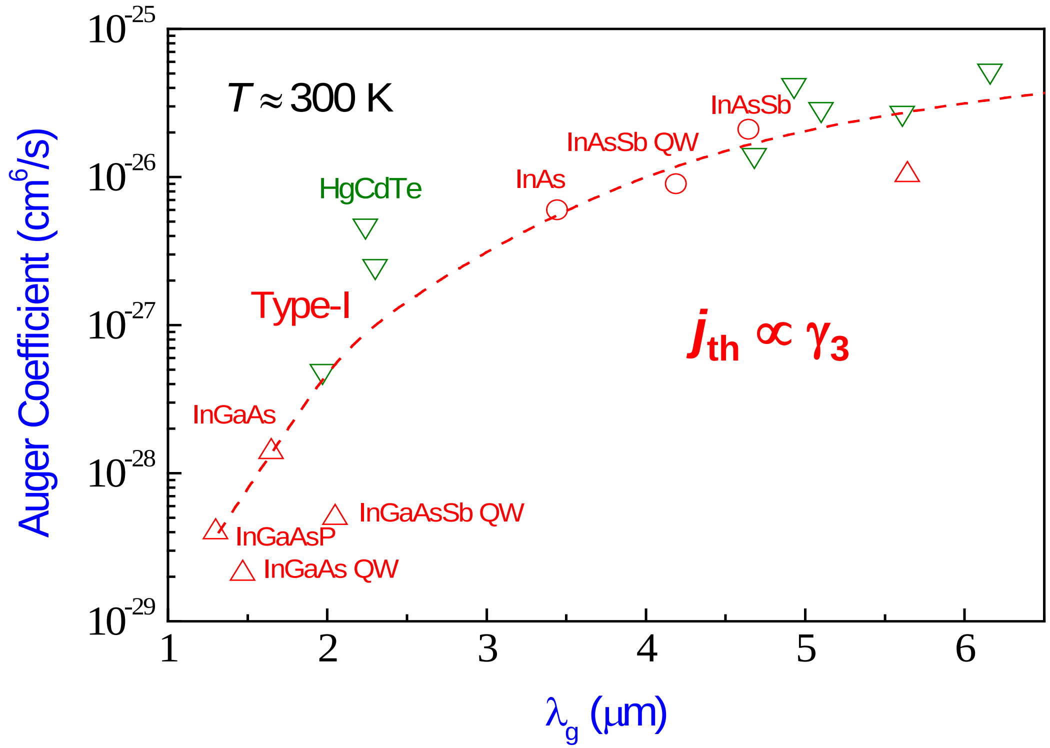
Cryogenic InAs mid-IR diode in 1963, but no RT cw for over 40 years – Why?

- ***Stubborn materials:*** GaSb growth & fab immature & intrinsically harder
- ***High loss:*** Free carrier absorption scales as λ^2 to λ^3
- ***Short upper-state lifetime:*** Rapid Auger decay of upper lasing level

nnp Auger process



Dominant decay in mid-IR semiconductors

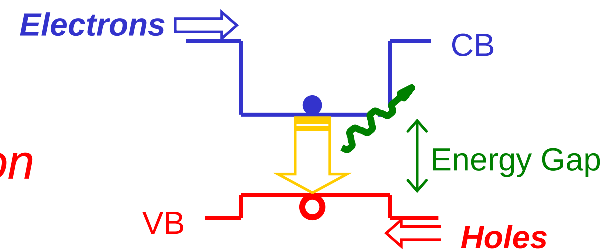


Lasing is literally orders of magnitude more challenging @ $\lambda > 3$ μm than $\lambda = 1$ μm!

2 Alternatives: **(1) Abandon the diode (QCL); (2) Improve the diode (ICL)**

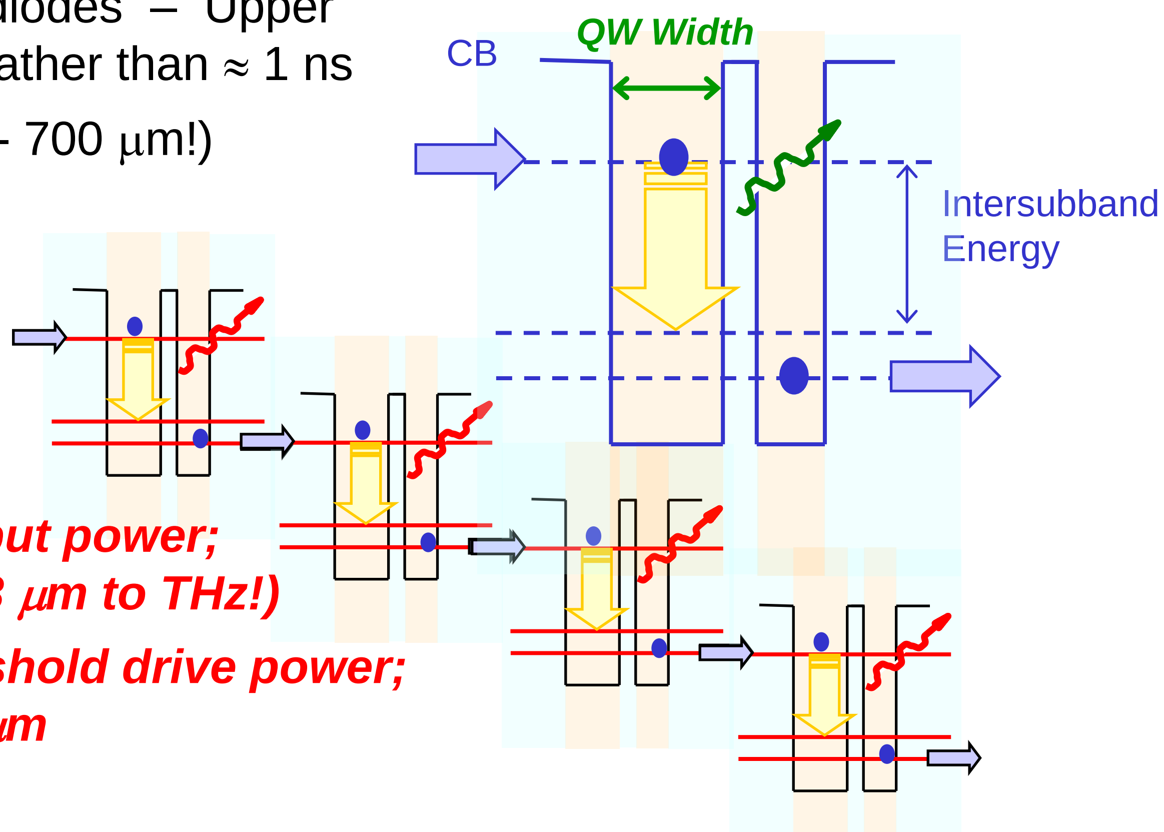
SOLUTION #1: ABANDON THE DIODE!
THE QUANTUM CASCADE LASER (QCL)

Rather than employing e-h recombination as in a conventional diode laser



QCL exploits optical transitions between *electron subbands in a QW – No holes, so not a diode*

- Very different regime from diodes – Upper lasing level lifetime ≈ 1 ps rather than ≈ 1 ns
- Tune λ with QW width (2.6 - 700 μm!)
- With cascade staircase, 1 electron in can yield 30-40 photons out!



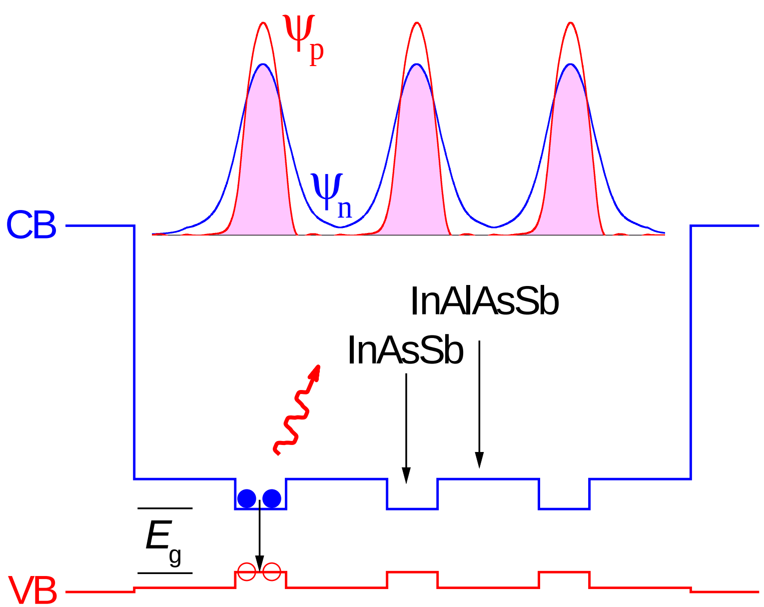
***Advantages:* (1) High cw output power;**
(2) Broad spectral coverage (3 μm to THz!)

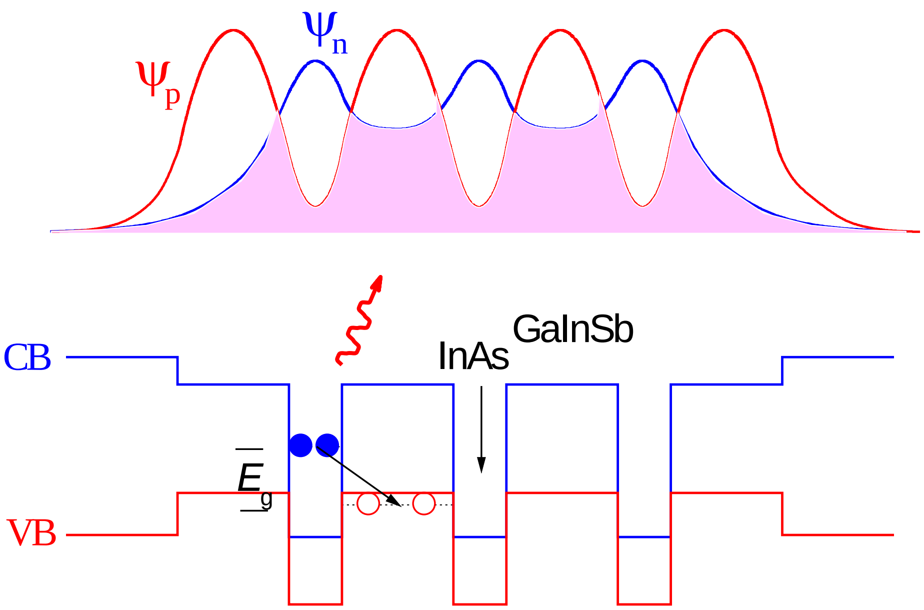
***Disadvantages:* (1) High threshold drive power;**
(2) More challenging @ λ < 4 μm

Any alternative?

HISTORICAL BACKGROUND:
TYPE-I vs. TYPE-II CONVENTIONAL DIODES

Type-I	Type-II
InAsSb/InAlAsSb QW *(MIT-LL,c.1993)*	InAs/GaInSb Superlattice *(HRL,1994)*





Advantage:

(1) Strong wavefunction overlap (high gain)

Disadvantages:

(1) Poor electrical confinement
(2) Limited wavelength range
(3) Short Auger lifetime

Disadvantage:

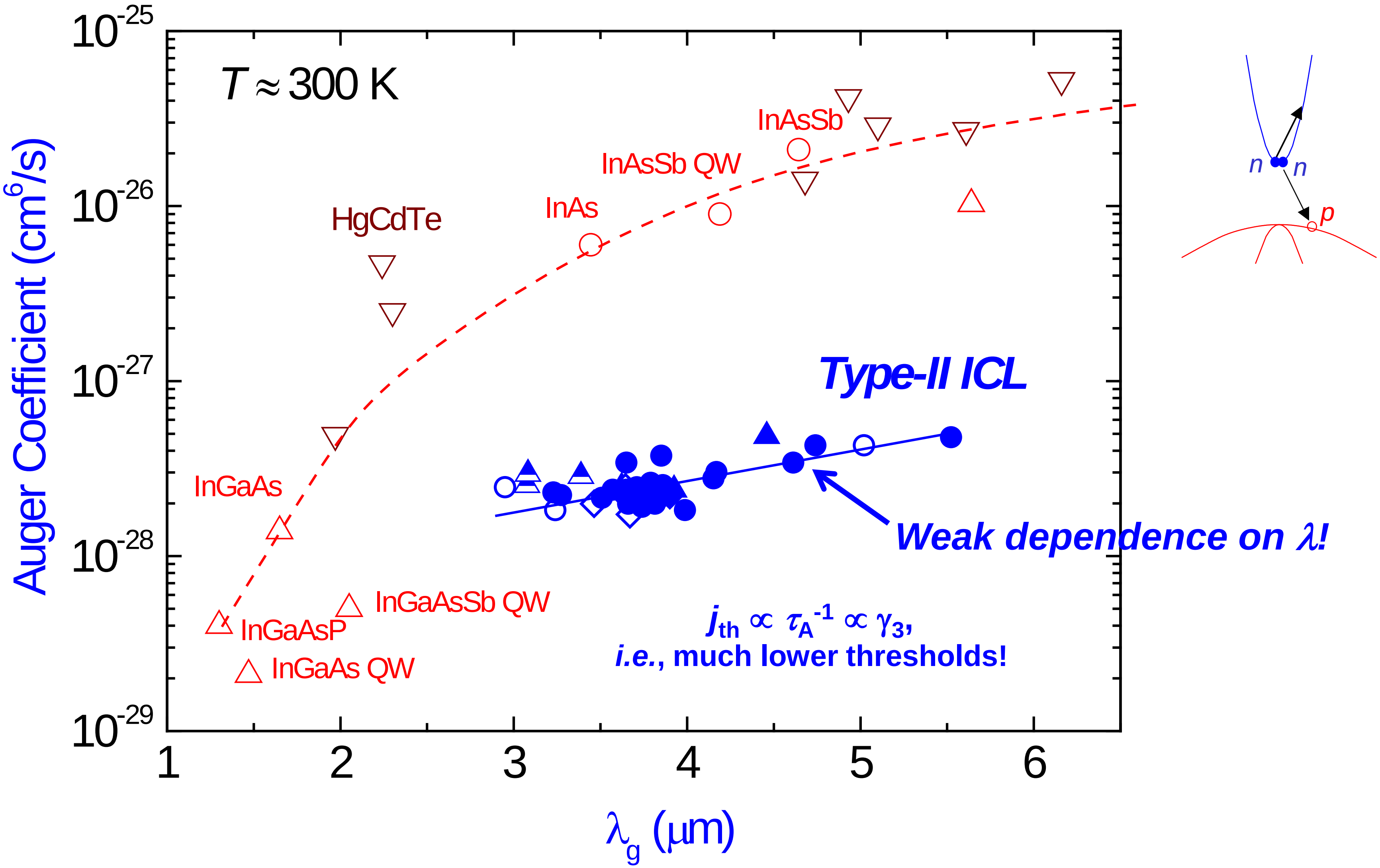
(1) Spatially indirect (but good gain for thin QWs)

Advantages:

(1) Excellent electrical confinement
(2) Access to much longer λ
(3) Suppressed Auger

LOWER THRESHOLDS VIA AUGER SUPPRESSION

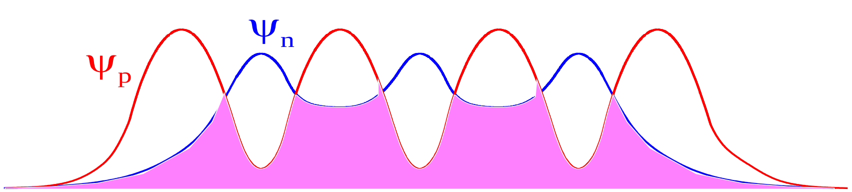
[Vurgaftman et al., JSTQE 19, 1200120 (2013)]



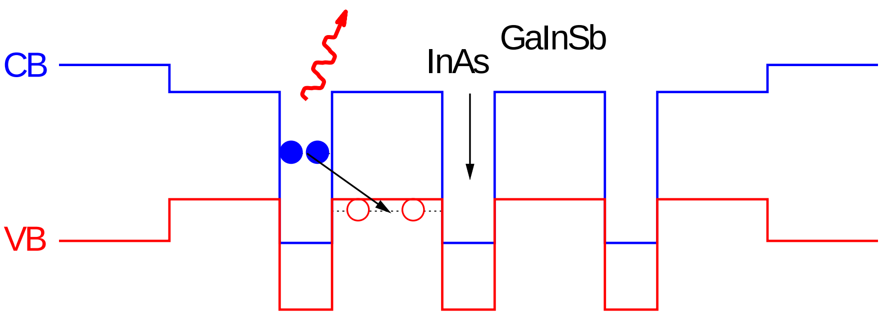
Consistent γ_3 for > 60 ICL wafers with 3, 5, 7, & 10 stages, numerous designs

TYPE-II SUPERLATTICE vs. TYPE-II QWs

Type-II Superlattice

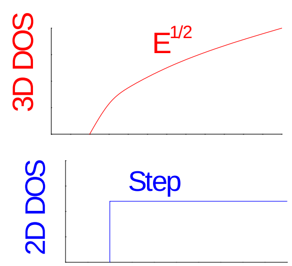


So much wf penetration that m_n^* nearly isotropic (3D)

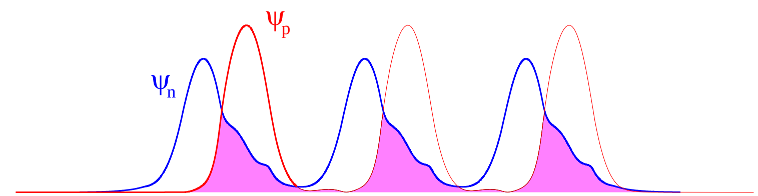


Advantages:
(1) Excellent electrical confinement
(2) Longer λ

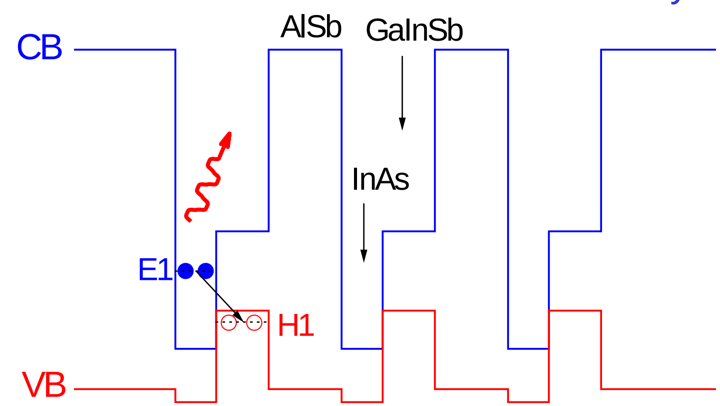
Disadvantage:
3D Density-of-States



3-Layer Type-II (NRL unp., *c*. 1994)



AlSb is barrier for both e & h – Now really 2D

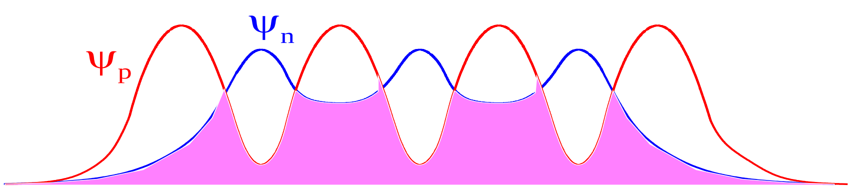


Advantage:
2D DOS for electrons & holes

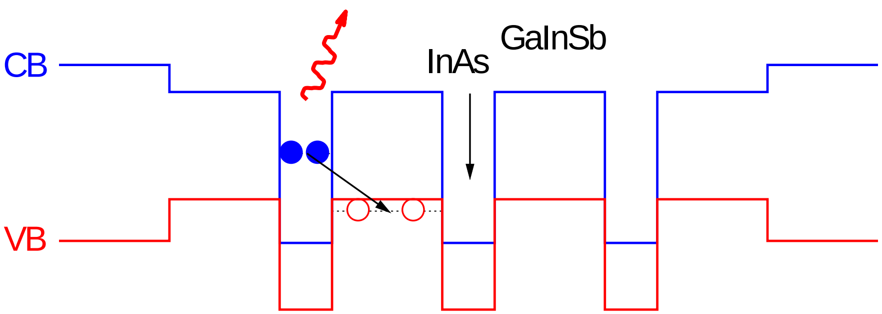
Disadvantage:
Reduced wavefunction overlap

TYPE-II SUPERLATTICE vs. TYPE-II QW

Type-II Superlattice



So much wf penetration that m_n^* nearly isotropic (3D)



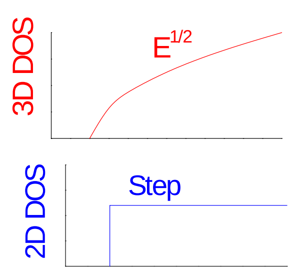
Advantages:

(1) Excellent electrical confinement

(2) Longer λ

Disadvantage:

3D Density-of-States



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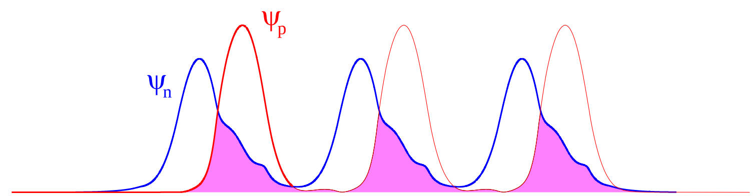
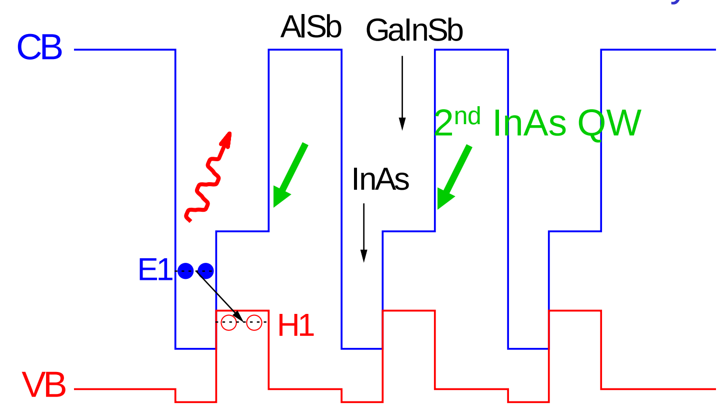


AlSb is barrier for both e & h – Now really 2D



Advantage:

2D DOS for electrons & holes

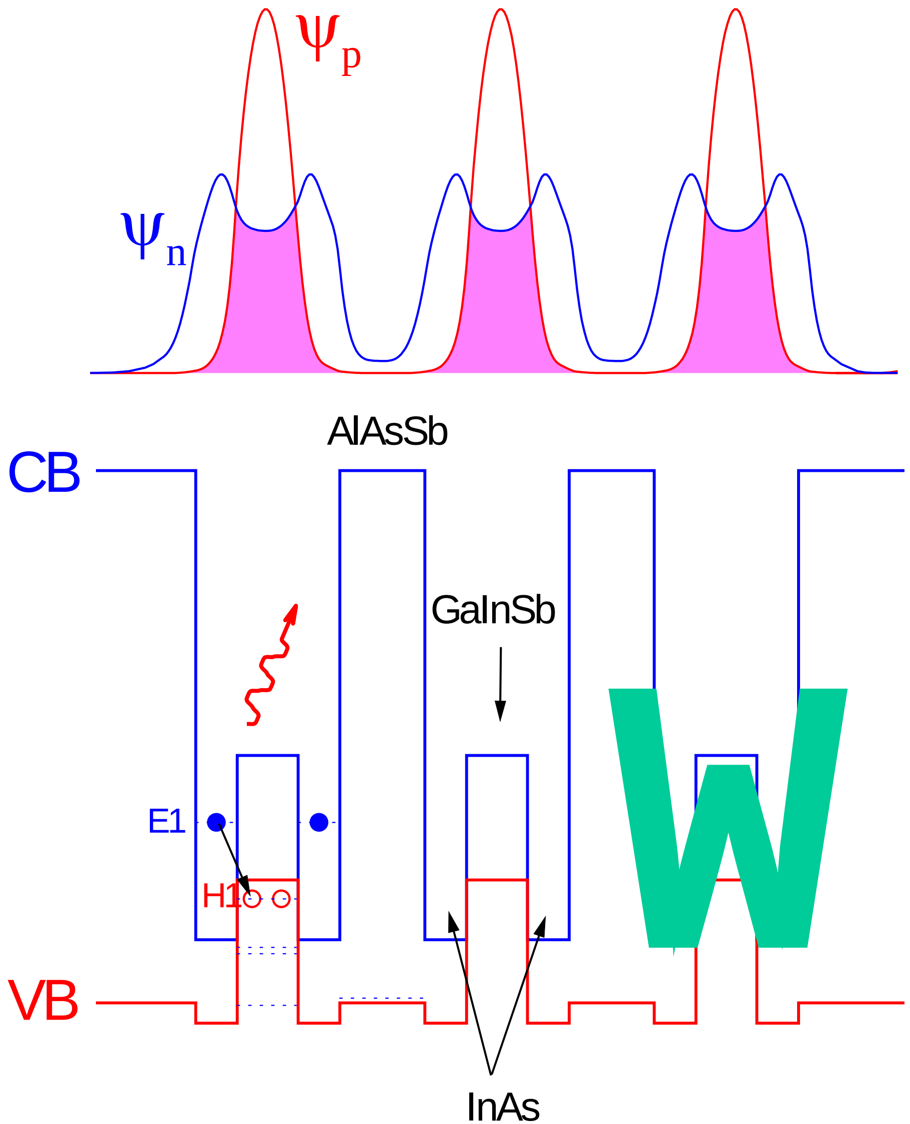
Disadvantage:

Reduced wavefunction overlap

Solution:

The Type-II "W" Laser

TYPE-II "W" LASER



ADVANTAGES:

(1) Strong wavefunction overlap
– For high gain

(2) 2D DOS for both electrons & holes

(3) Excellent electrical confinement

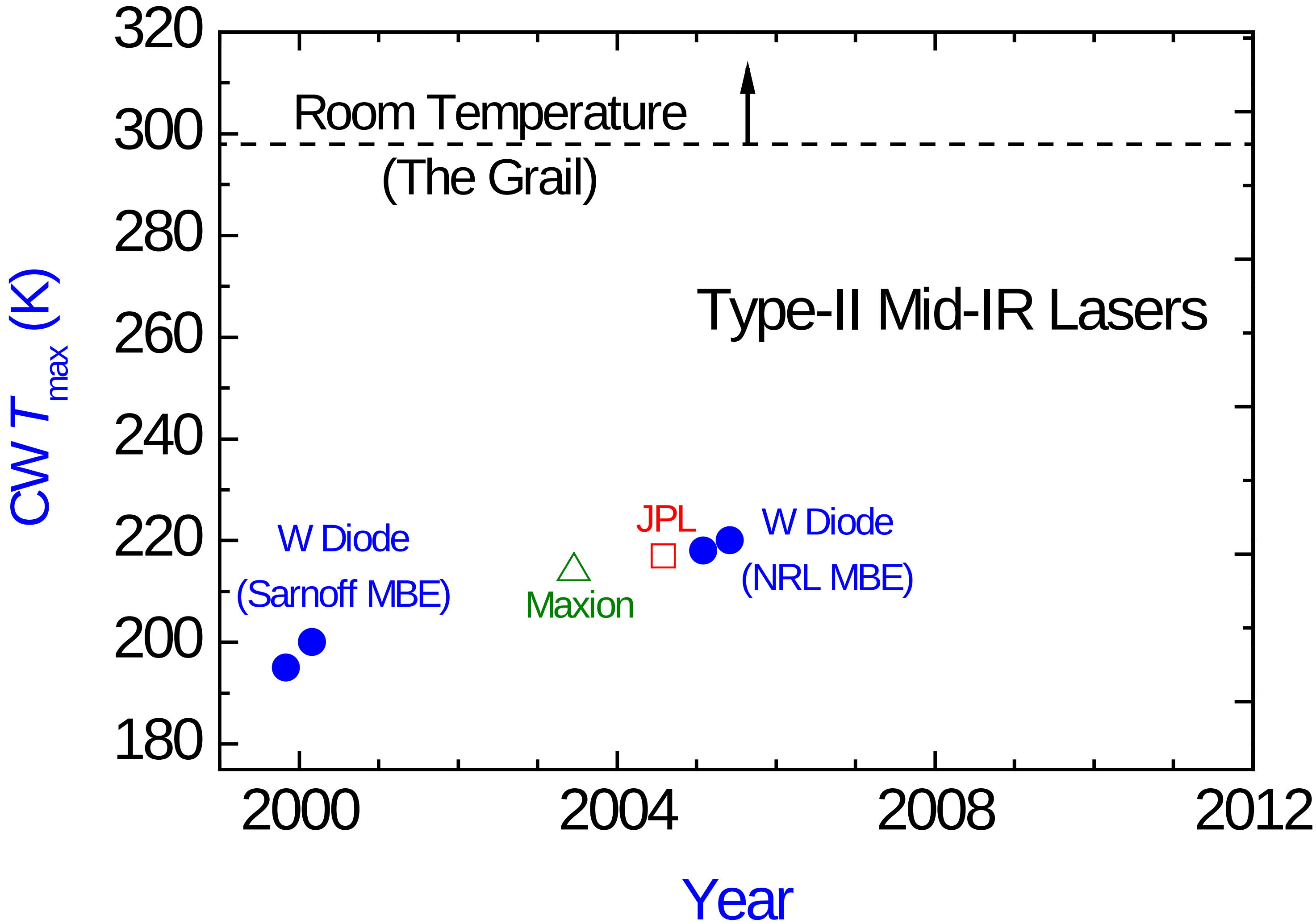
(4) Arbitrarily-long wavelength

(5) Auger suppression

First interband mid-IR laser to operate at room temperature (Pulsed optical pumping, 1996)

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

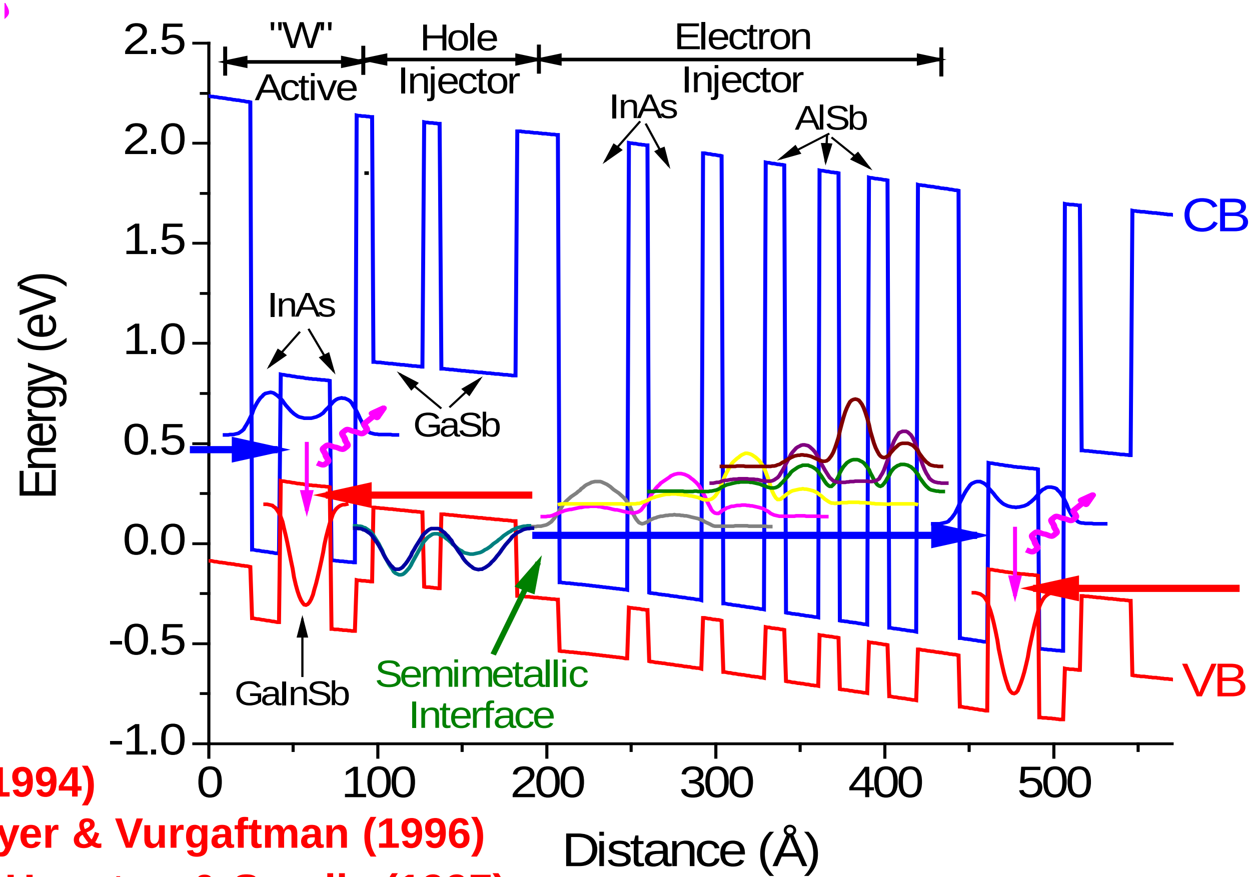
CW T_{max} TIMELINE (TO 2005)



Nonetheless, by 2005 prospects for mid-IR diodes operating cw @ RT seemed remote – But another card to play…

THE INTERBAND CASCADE LASER

Hybrid of conventional diode (*Interband* active transitions) & QCL (*Cascaded* stages)



1st Proposed: **R. Q. Yang (1994)**

Design Improvements: **Meyer & Vurgaftman (1996)**

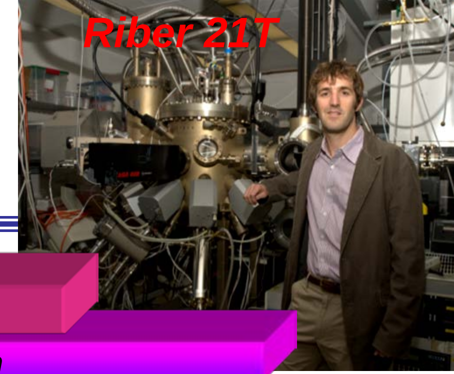
1st Experimental Demo: **U. Houston & Sandia (1997)**

Further Development: **ARL, Maxion, JPL, U. Oklahoma, U. Würzburg, Nanoplus, Wroclaw U.**

1st NRL ICL growth: **2005**

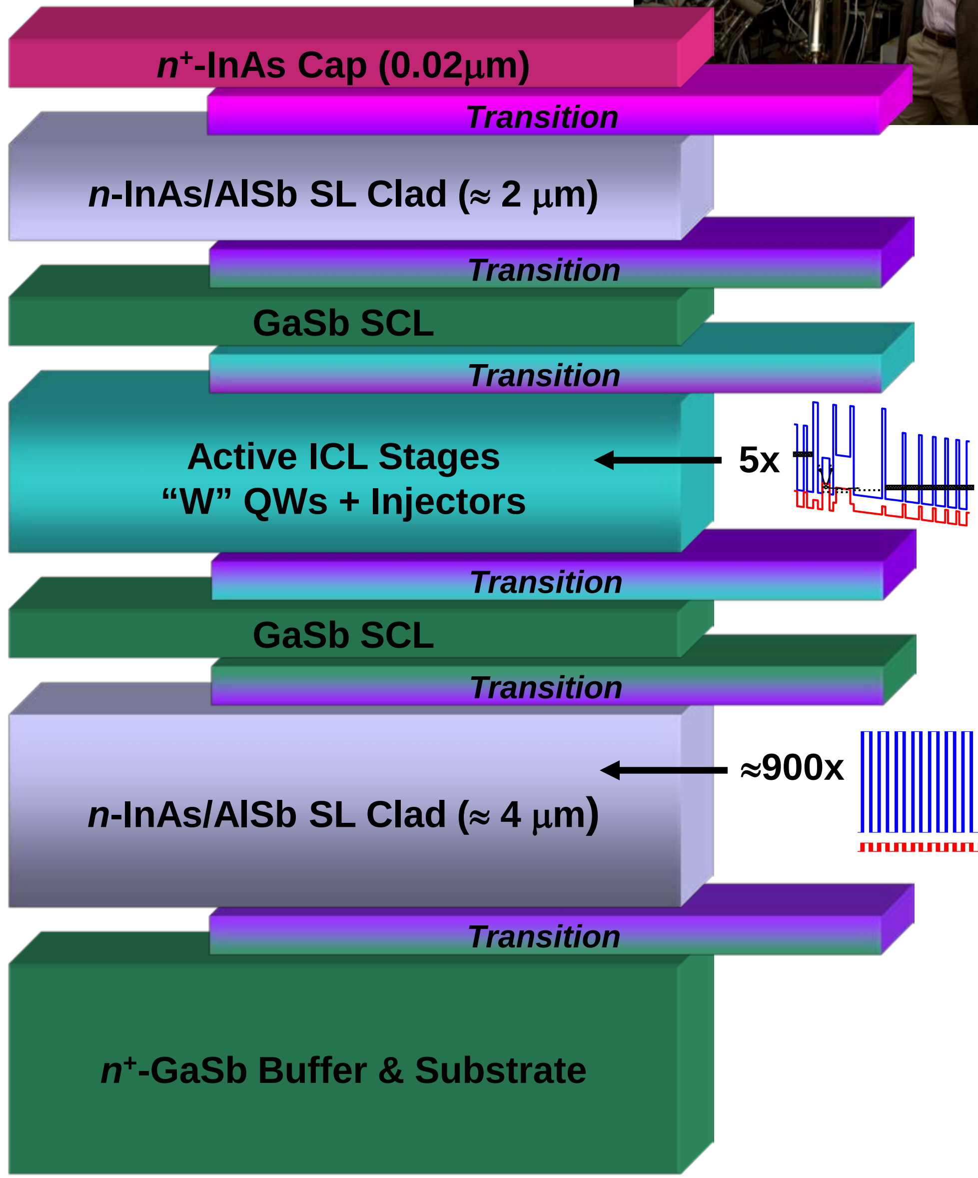
Type-I ICLs: **Proposed NRL (1996), Demo Sandia (1998), 3 Growths NRL (2011), Improved Designs NRL (2011), Demos: SUNY (2013), NRC Canada & Oklahoma (2014)**

FULL LAYERED STRUCTURE

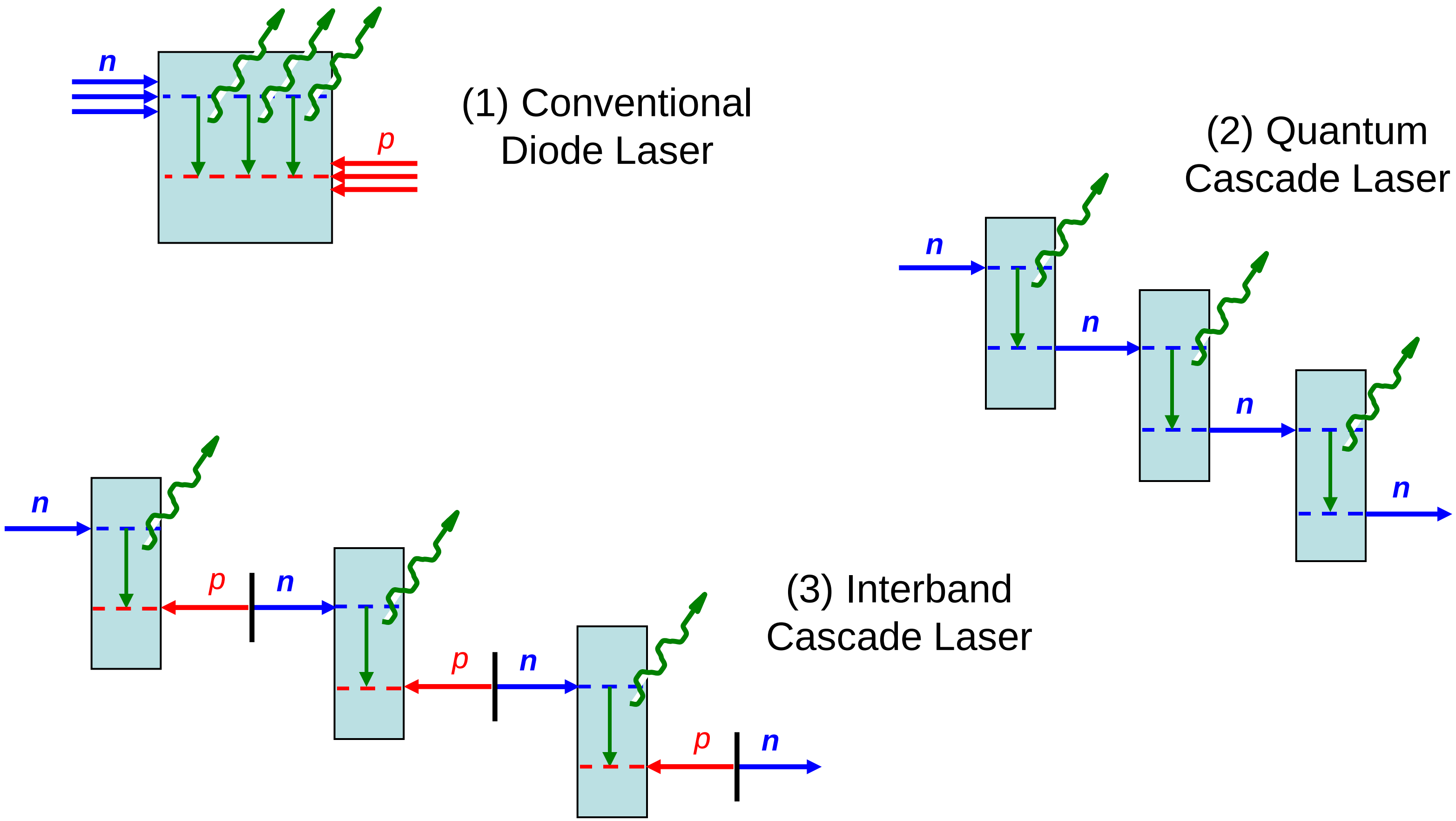


Active ICL stages surrounded by separate confinement & optical cladding layers, each separated by transition regions

- ***Lattice-Matching:*** Each region carefully strain-compensated to minimize dislocations
- ***Full structure:*** 7–8 μm thick & > 3000 layers (takes 7-8 hours to grow)
- ***Yield:*** Surprisingly high – Most NRL ICL wafers produce high-quality lasers

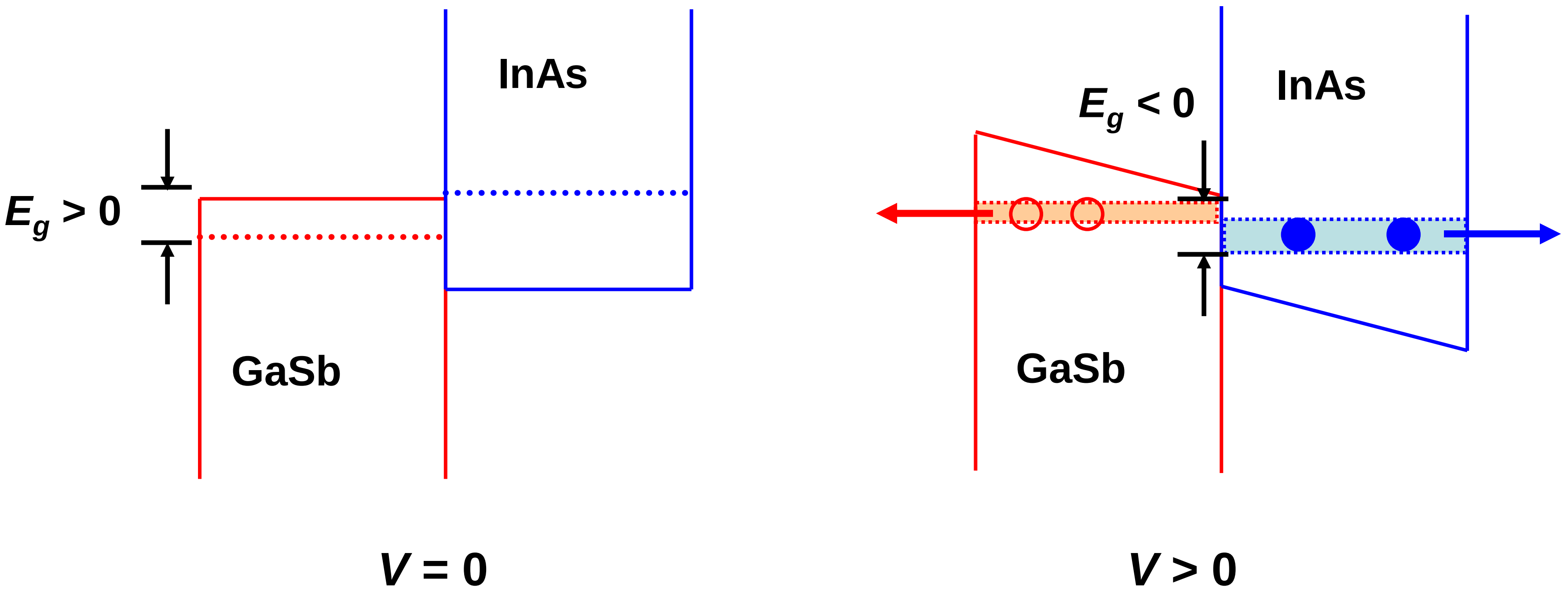


3 DISTINCT WAYS TO PROVIDE CARRIERS FOR POPULATION INVERSION



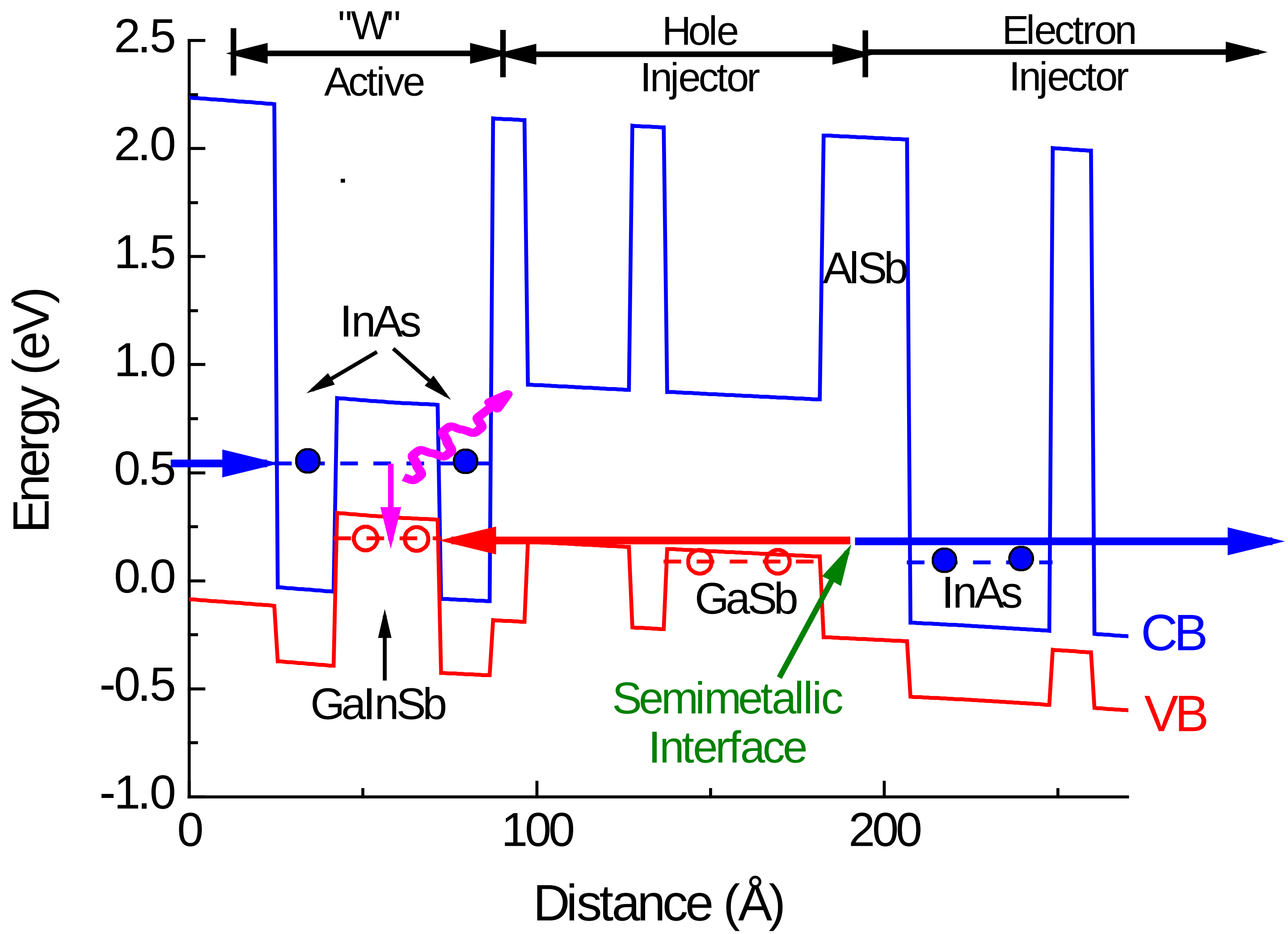
ICL uniquely generates holes and electrons *internally* – How?

TYPE-II BAND ALIGNMENT @ InAs/GaSb INTERFACE



External bias applied to small-gap type-II InAs/GaSb interface induces semimetallic band alignment – *Creates electrons & holes!*

TYPE-II ALIGNMENT IN THE LASER



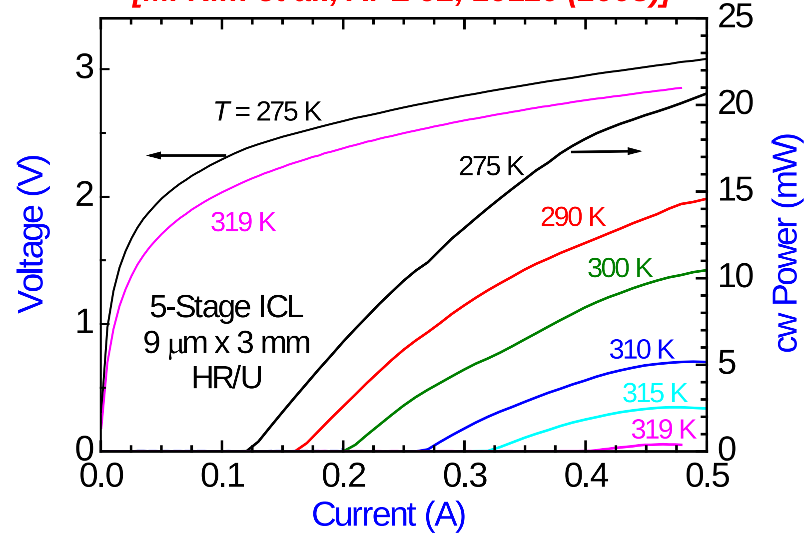
Semimetallic interface supplies carriers to electron & hole injectors

RT CW ICLs (2008)

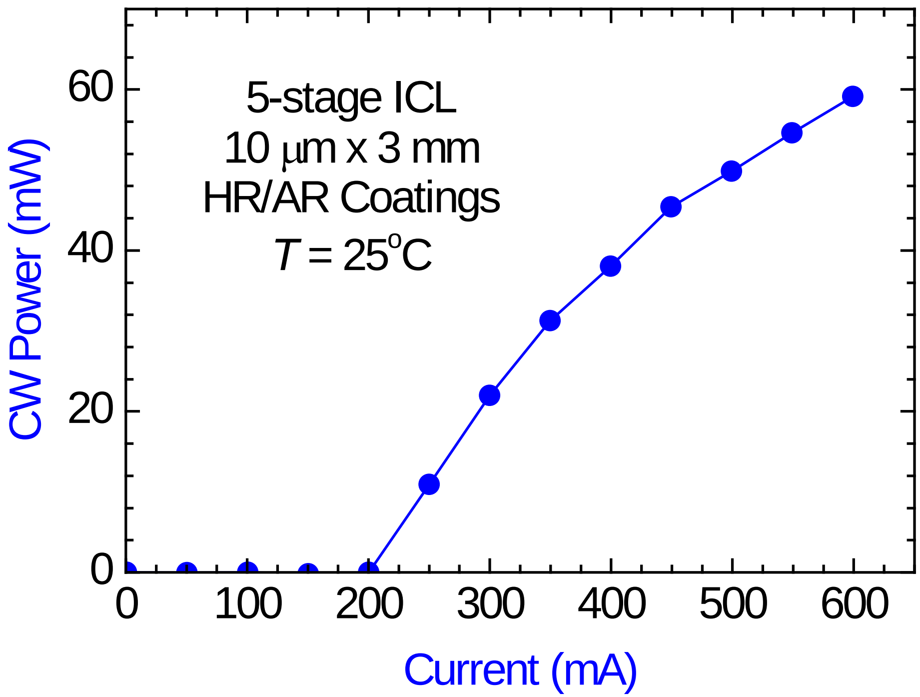
After initial NRL MBE growth of ICLs in 2005, iterative reduction of j_{th} led to 1st RT cw in 2008:

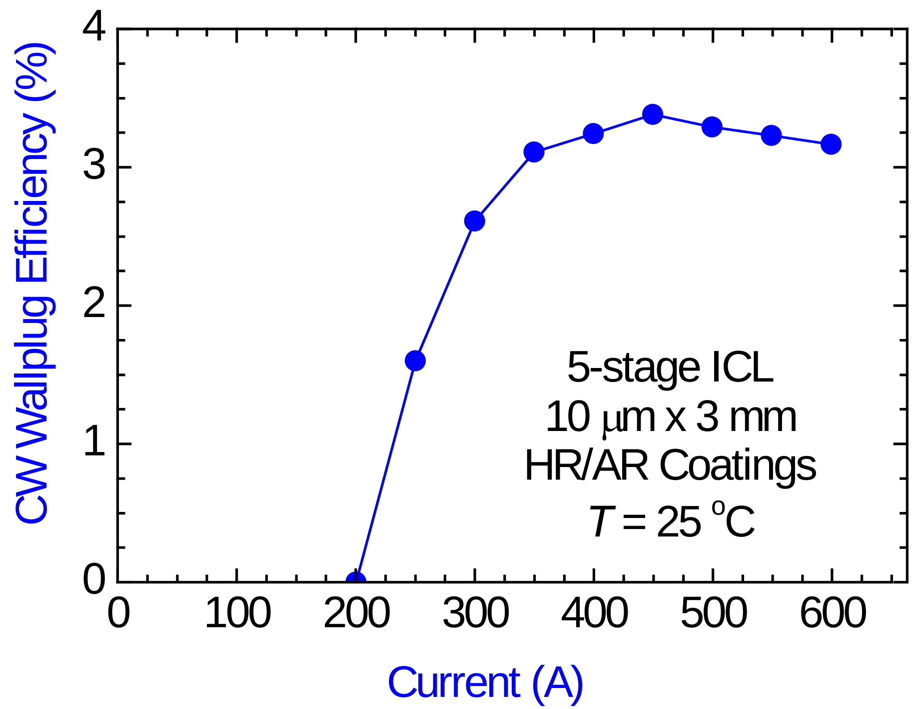
P_{max} = 10 mW; WPE = 0.7% @ P_{max}

[M. Kim et al., APL 92, 19110 (2008)]



With improved ridge processing (2009):

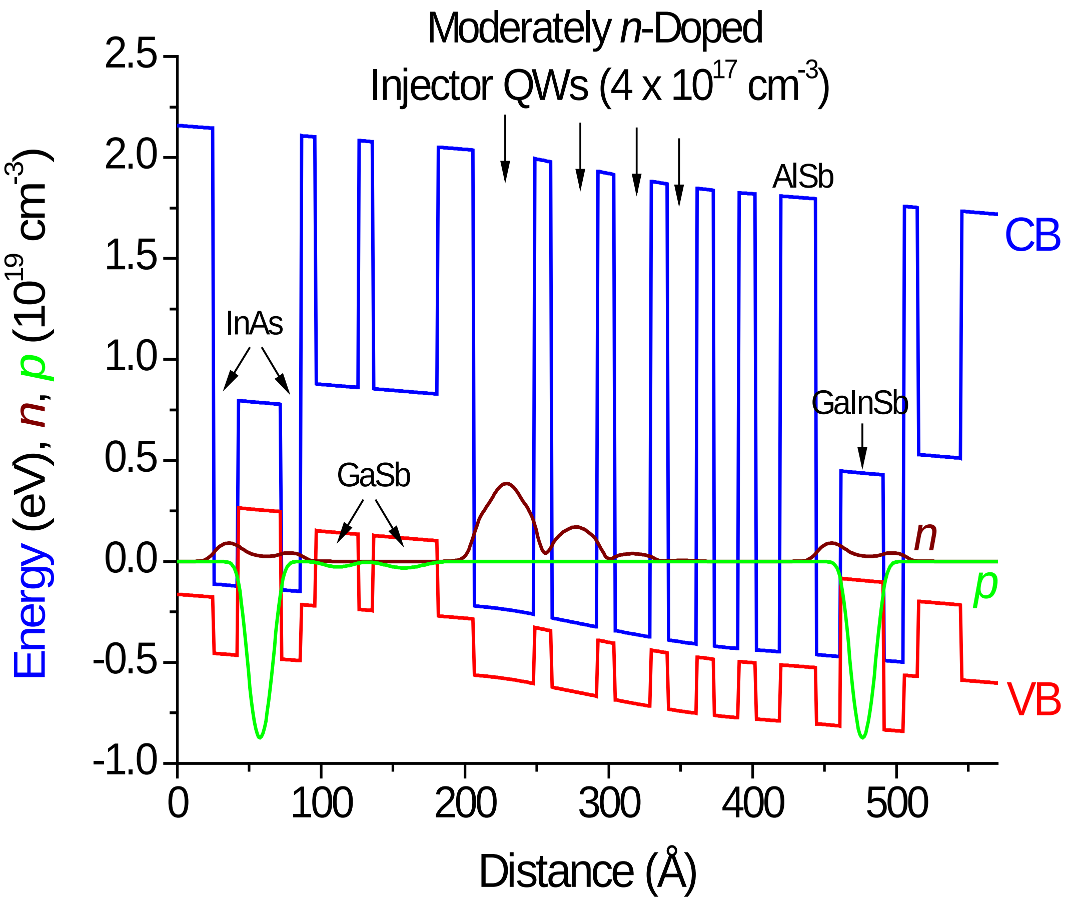




Best as of 2009: **P_{max} = 59 mW, WPE = 3.1% @ P_{max}**

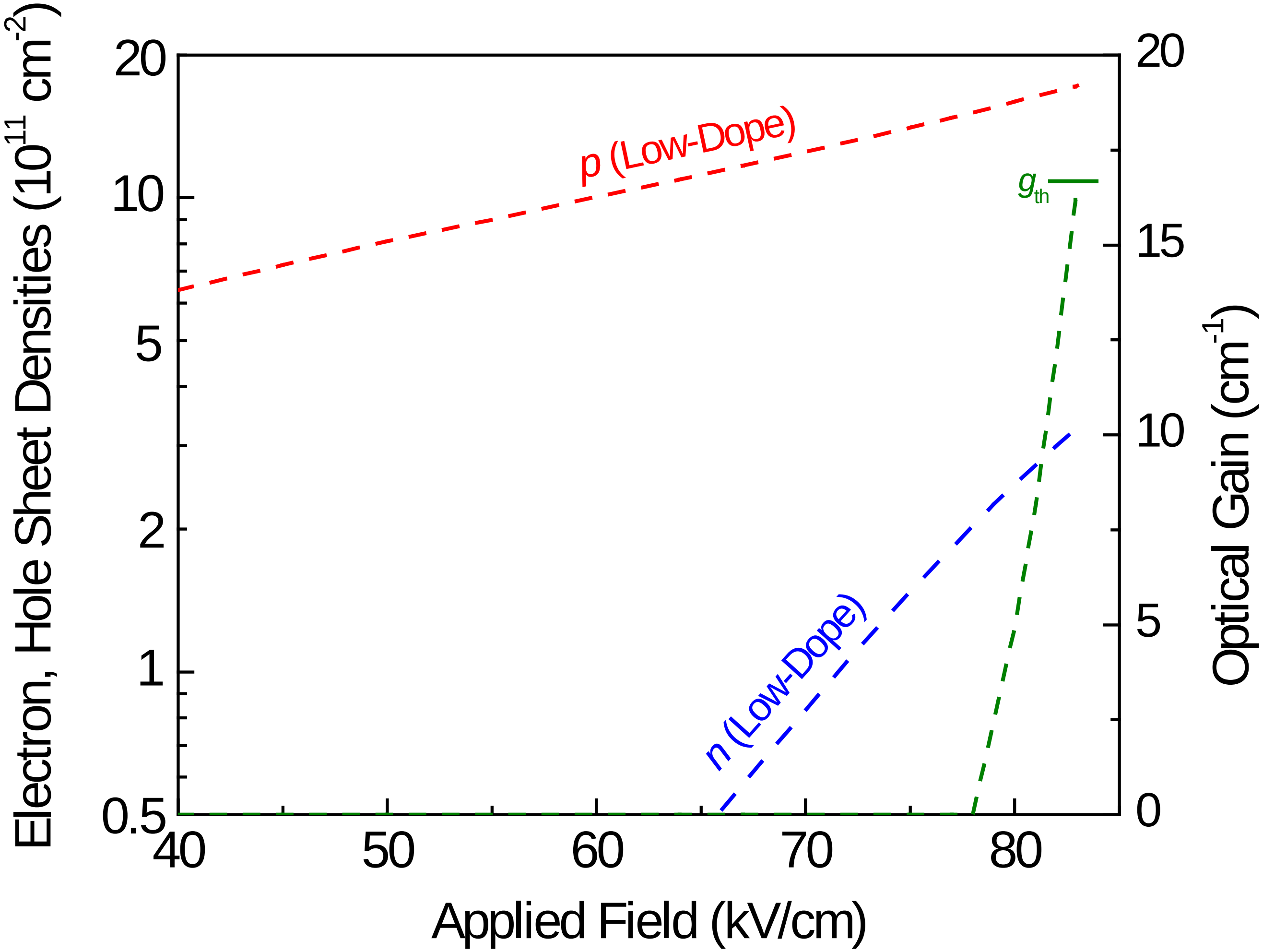
2010: A SIGNIFICANT DESIGN FLAW REMAINED

NRL simulations revealed that conventional designs with moderately-doped (≈ 4 x 10^{17} cm^{-3}) injector QWs suffered from serious population imbalance in active QWs



Even though more electrons than holes throughout the stage (due to *n*-doping of injector), most electrons populate injector while most holes populate active HQW

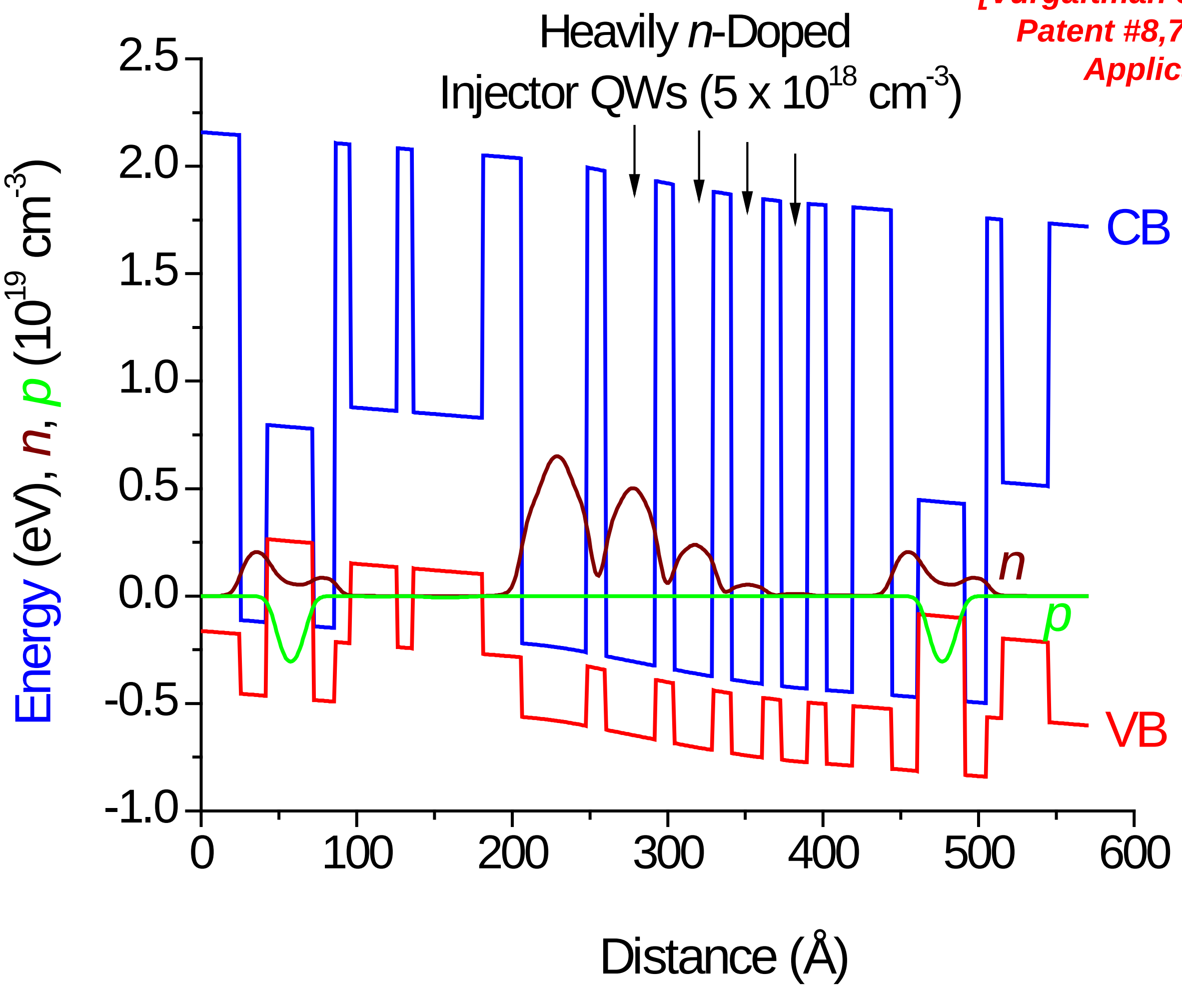
DENSITIES & GAIN vs. BIAS



> 5x more holes than electrons in active QWs at threshold – Consequence was excessive internal loss & Auger non-radiative decay

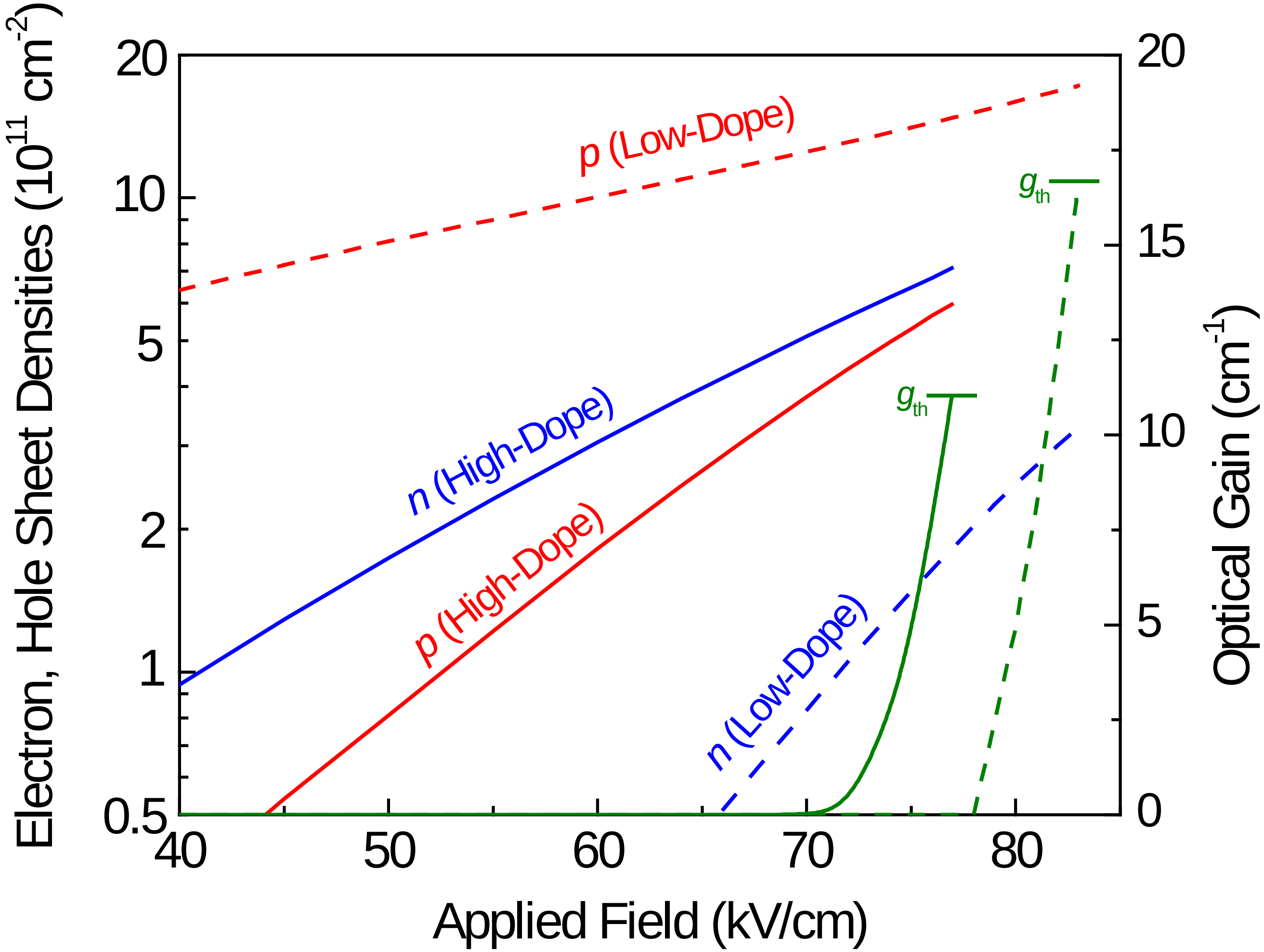
SOLUTION: INCREASE INJECTOR DOPING LEVEL BY > ORDER OF MAGNITUDE

[Vurgaftman et al., Nature Com. 2, 585 (2011); U.S. Patent #8,798,111 (2014); International Patent Application PCT/US12/29396 (2012)]



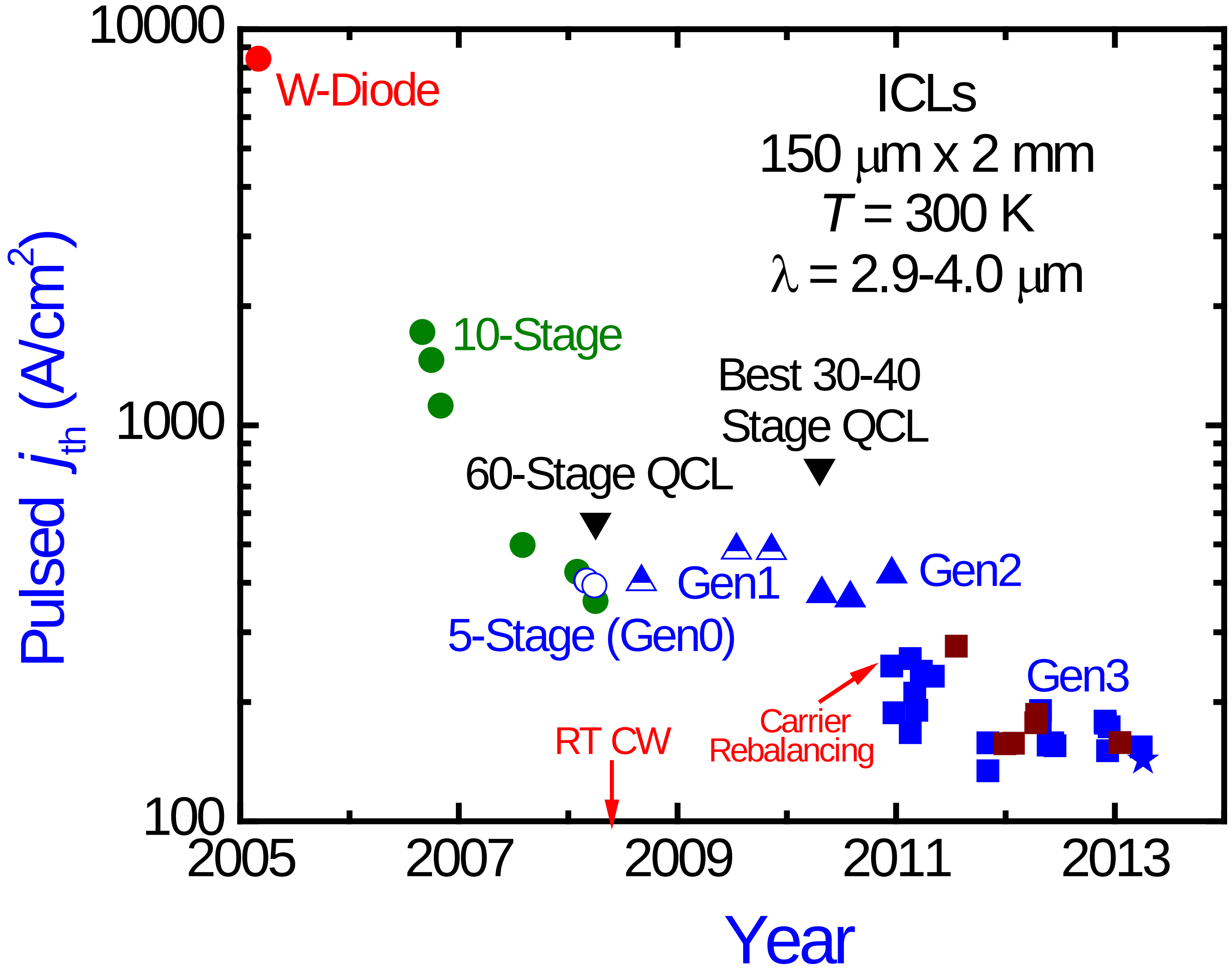
Heavier n-doping of injector "rebalances" active electron & hole populations, to make them roughly equal

DENSITIES & GAIN vs. BIAS (REBALANCED)



Simulations predicted rebalancing should enable lasing at much lower carrier concentration, plus longer Auger lifetime & lower loss (because much lower p_{th})

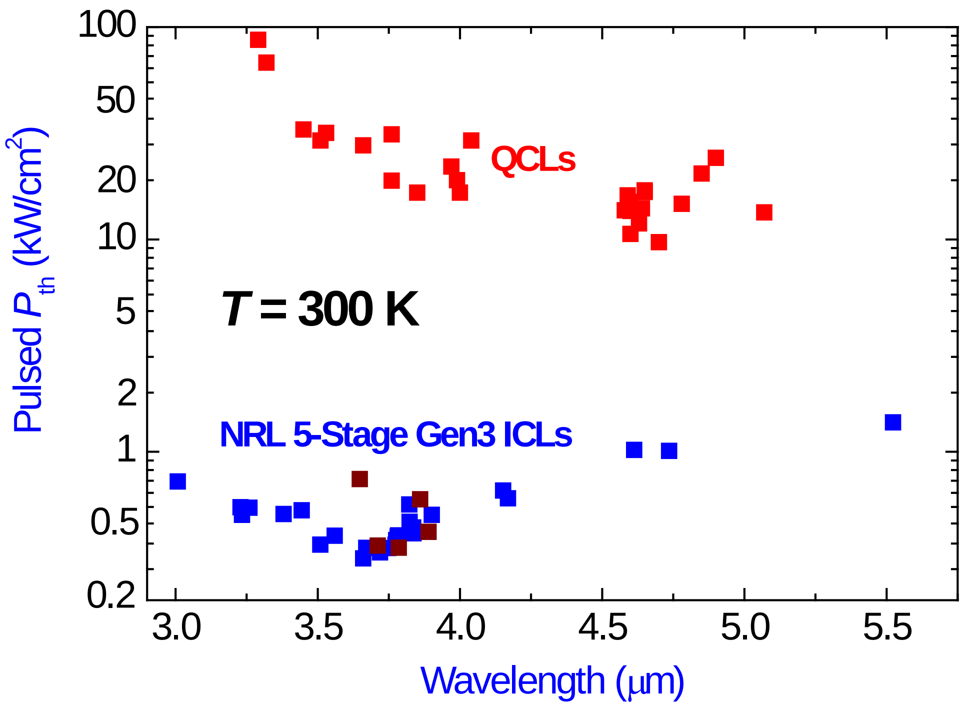
EXPERIMENTAL TEST:
REBALANCING EFFECT ON THRESHOLD



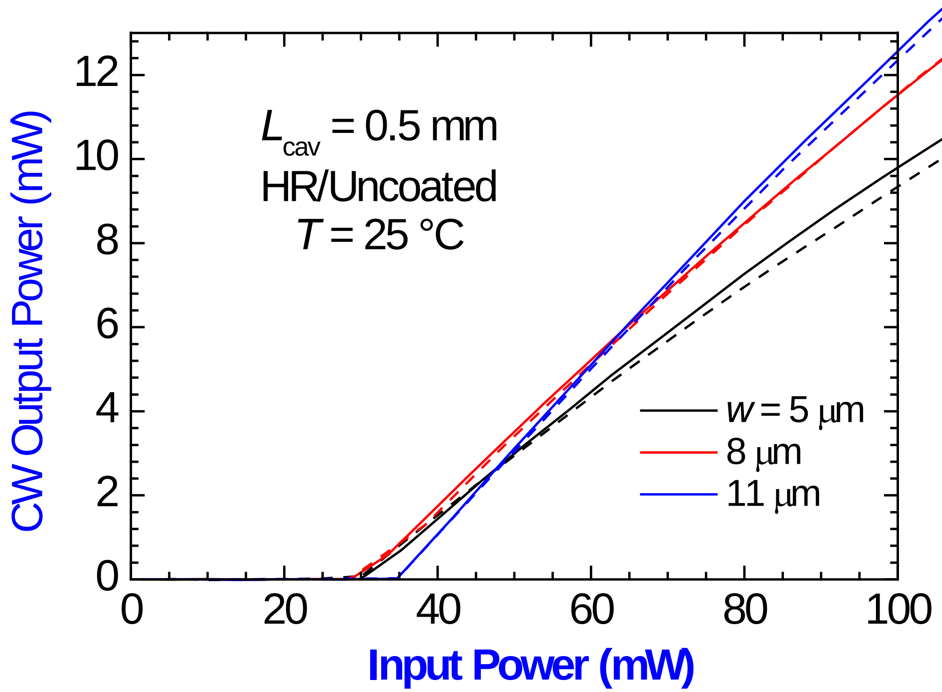
Dramatic threshold reduction compared to all previous

ICL SPECTRAL RANGE & LOW DRIVE POWER

Threshold power density:
$P_{th} = V_{th} \times j_{th}$



[Vurgaftman et al., Nature Com. 2, 585 (2011)]



Power density thresholds 30x lower than record QCL results

CW operation to *T* = 48 °C @ λ = 5.7 μm

T = 25 °C: **Input for lasing < 30 mW**

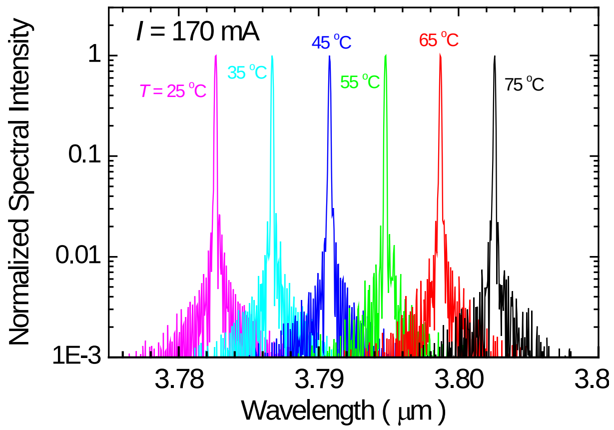
Best QCL result: **400 mW (Alpes)**

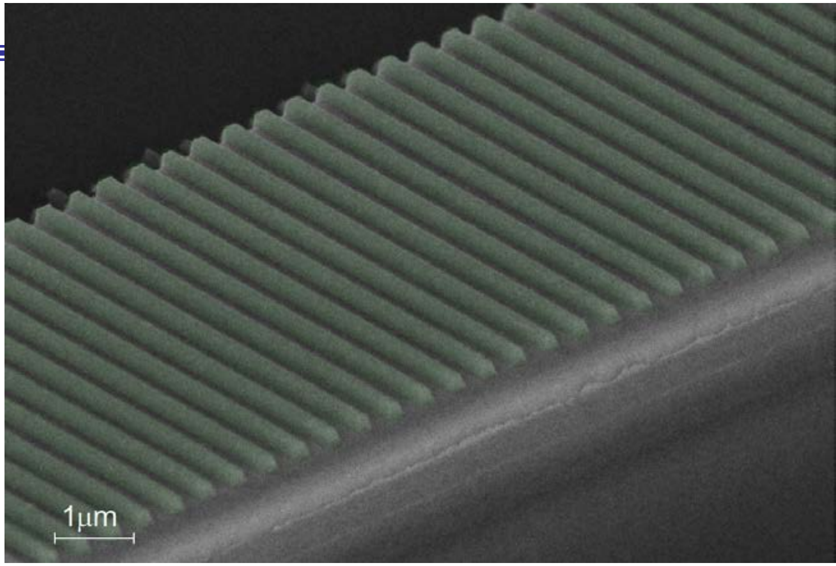
Critical for battery-operated, hand-held, solar-powered, etc.

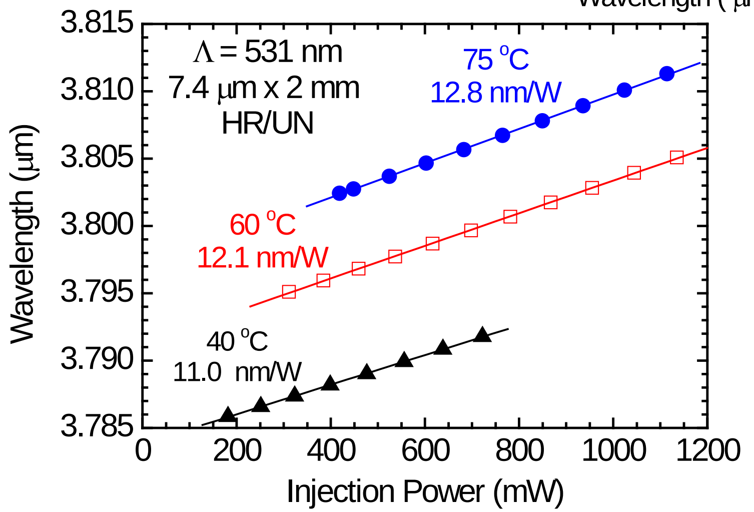
SINGLE-MODE DISTRIBUTED FEEDBACK ICLs

[Kim et al., APL 101, 061104 (2012)]

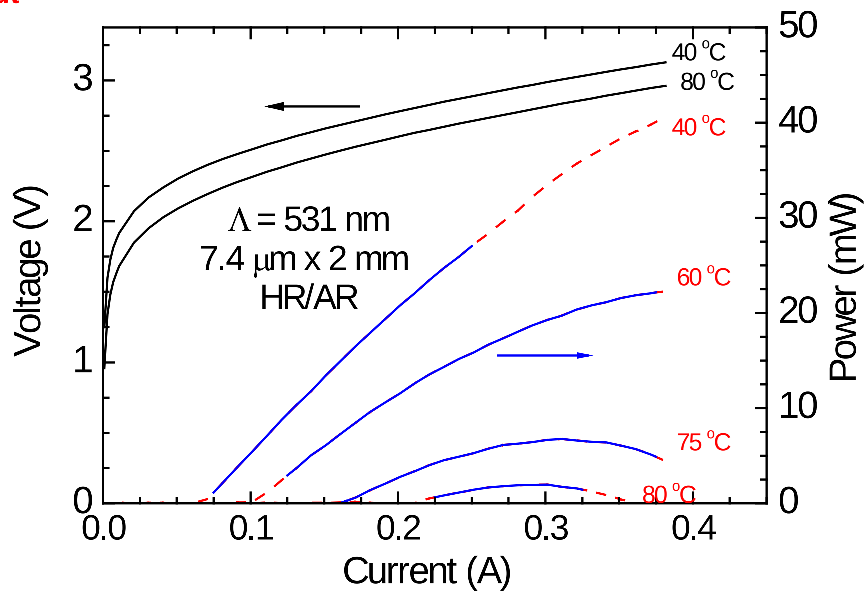
Several architectures explored @ NRL – Here DFB fabricated by etching grating into deposited Ge





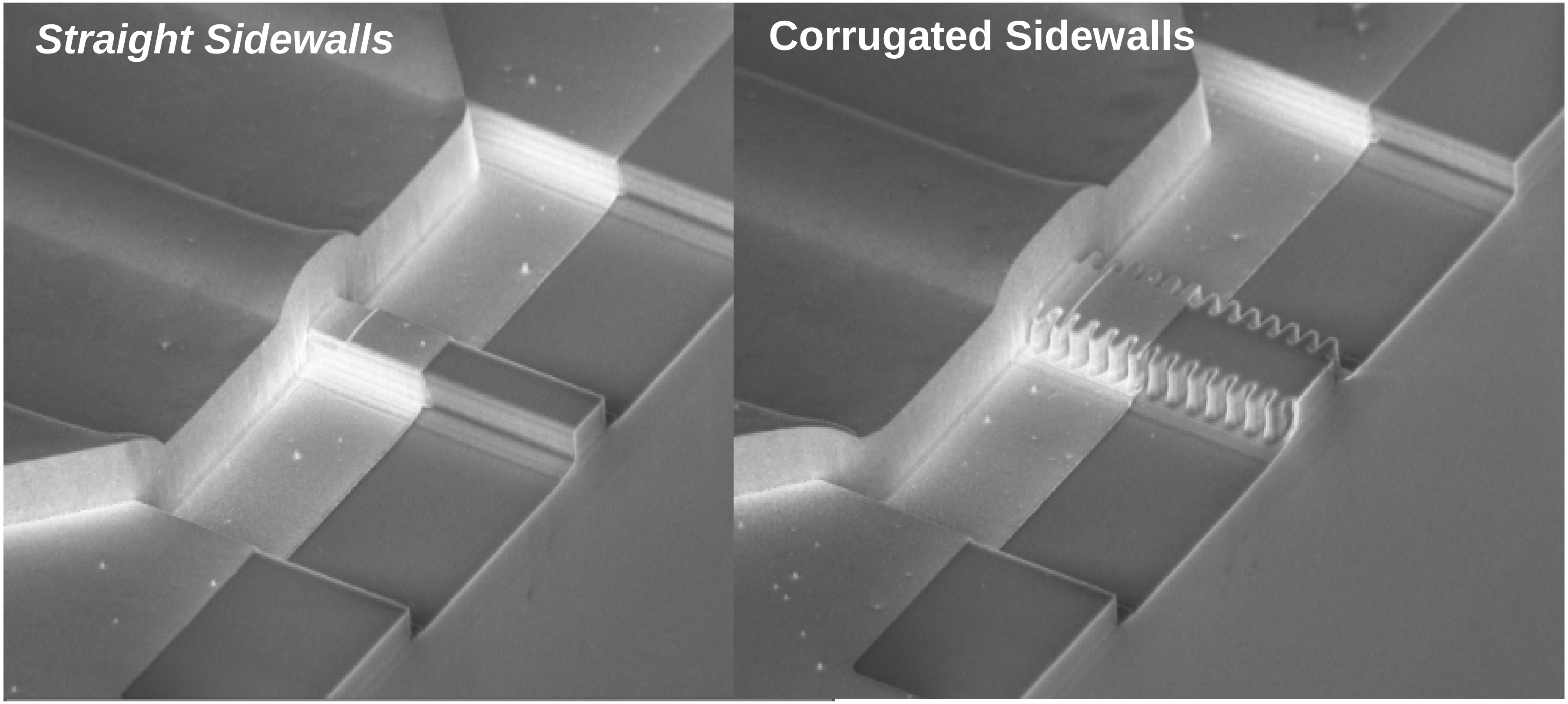


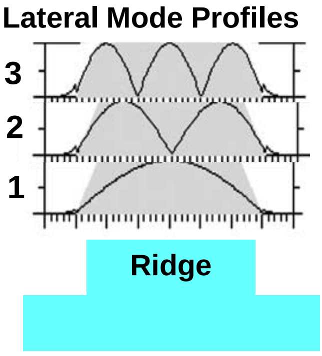
P_{out} = 27 mW @ T = 40 ºC, 1 mW @ 80 ºC



Single-mode tuning with temperature: 21.5 nm
with current: 10 nm

CORRUGATED-SIDEWALL ICLs

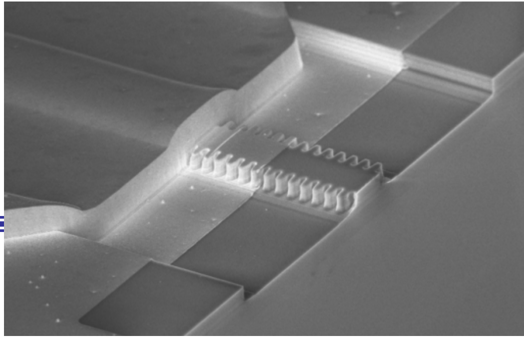




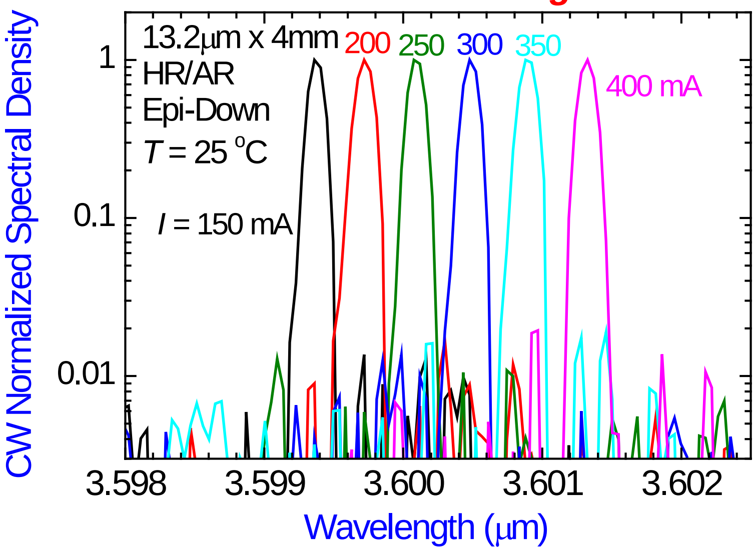
4th-order grating provides distributed feedback

Corrugations also suppress higher-order lateral modes for enhanced brightness

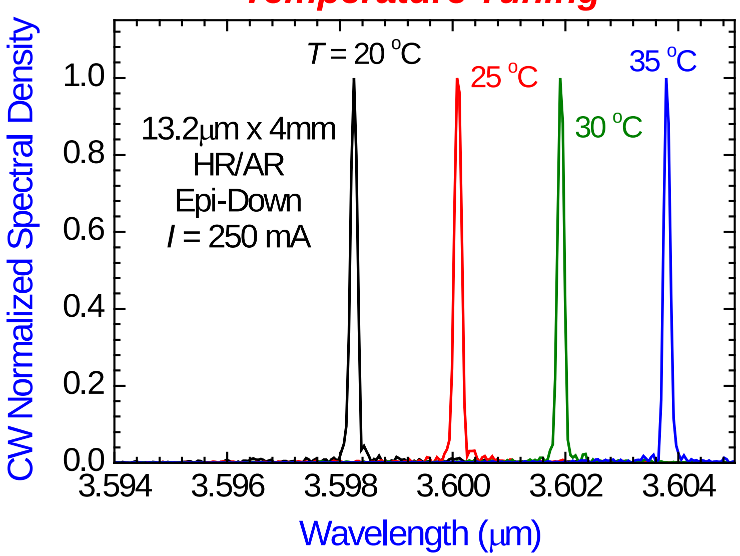
CORRUGATED-SIDEWALL DFBs



Current Tuning

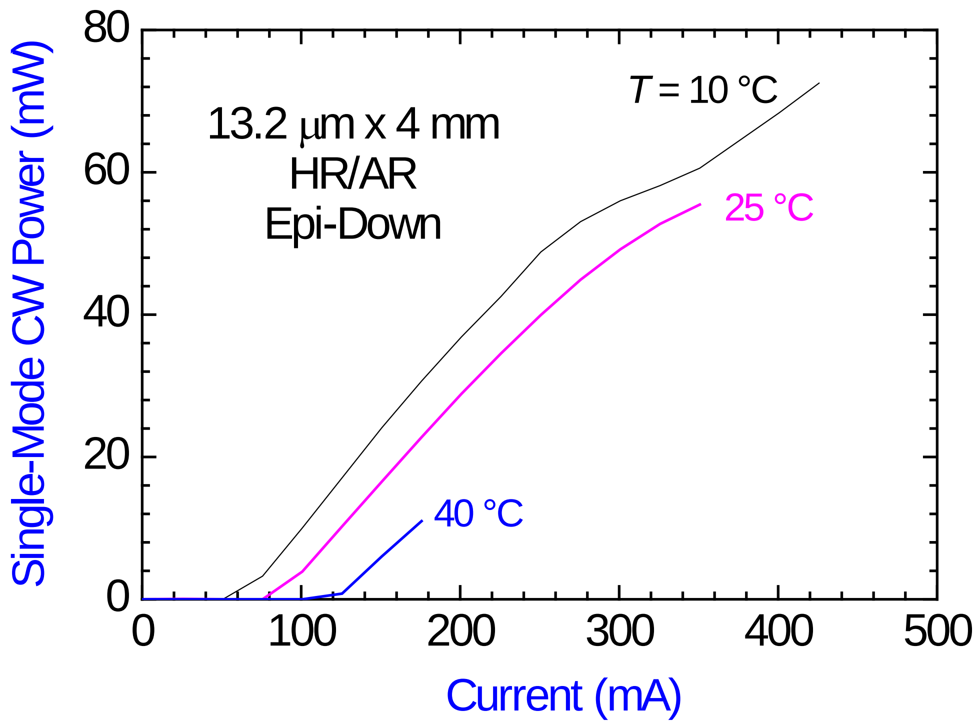


Temperature Tuning



[Vurgaftman et al., JSTQE 19, 1200210 (2013)]

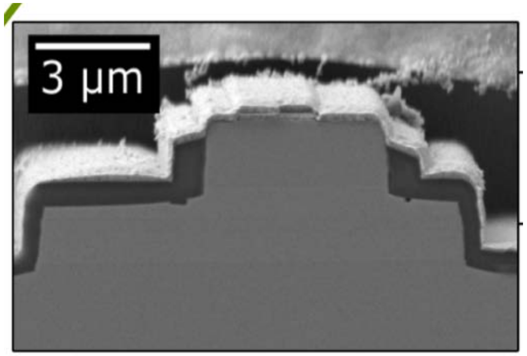
FWHM ≤ 0.15 nm (FTIR-limited)
SMSR ≈ 17-20 dB
55 mW cw in single spectral mode @ T = 25 ºC



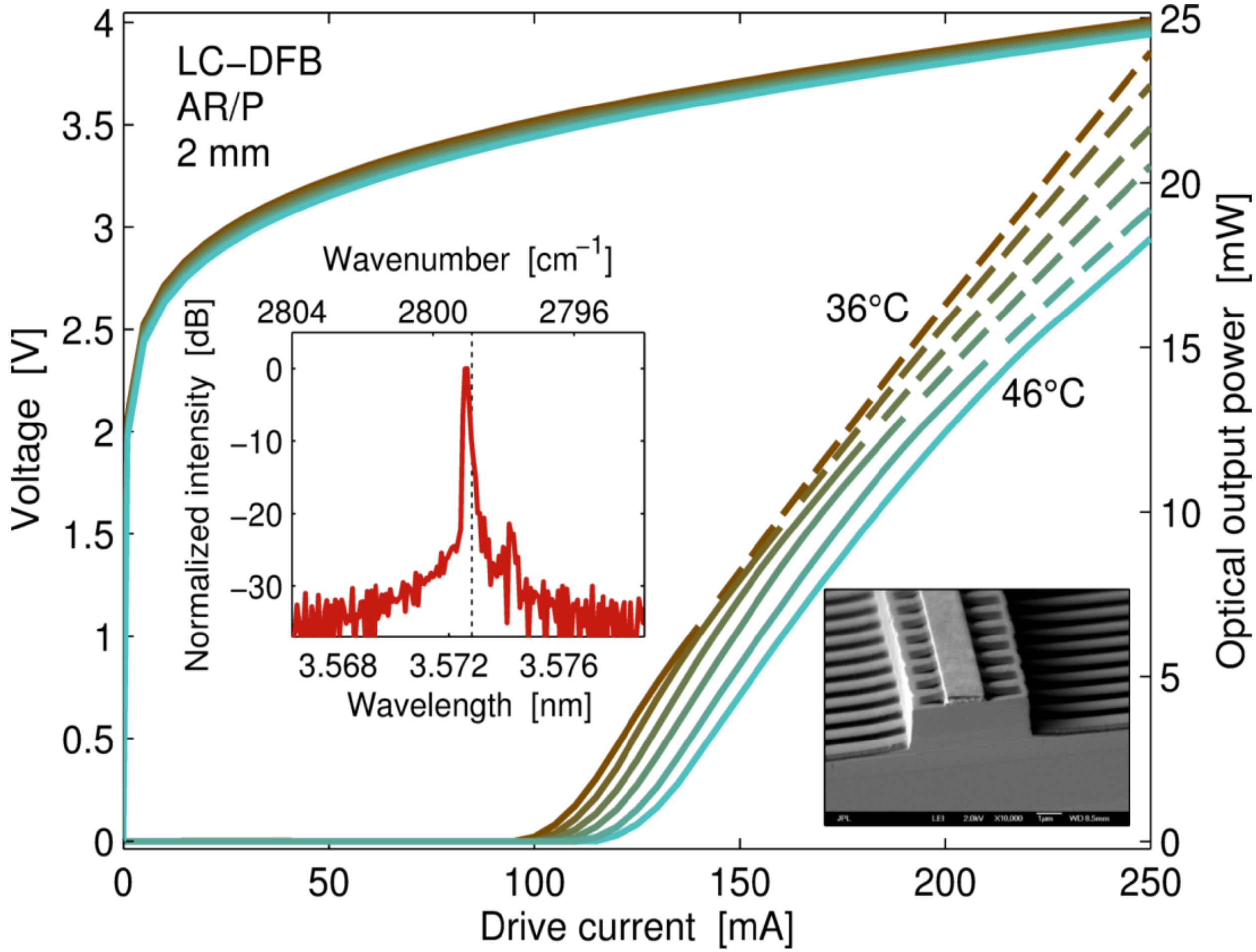
JPL DFBs

Grown @ NRL, Processed & tested @ JPL: **2nd-order side grating yields single mode**

[Forouhar et al., APL 105, 051110 (2014)]



Double ridge provides less abrupt index step



P_{max}^{cw} = 18 mW @ T = 46 ºC

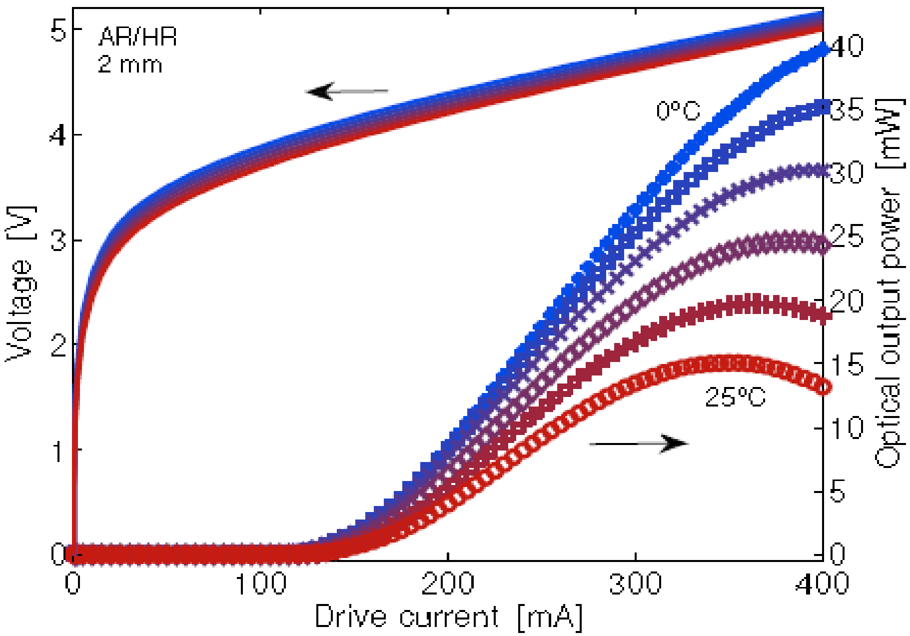
Threshold drive power < 400 mW @ 36 °C

Lifetime testing: > 10,000 hrs. cw operation @ 40 °C with negligible degradation

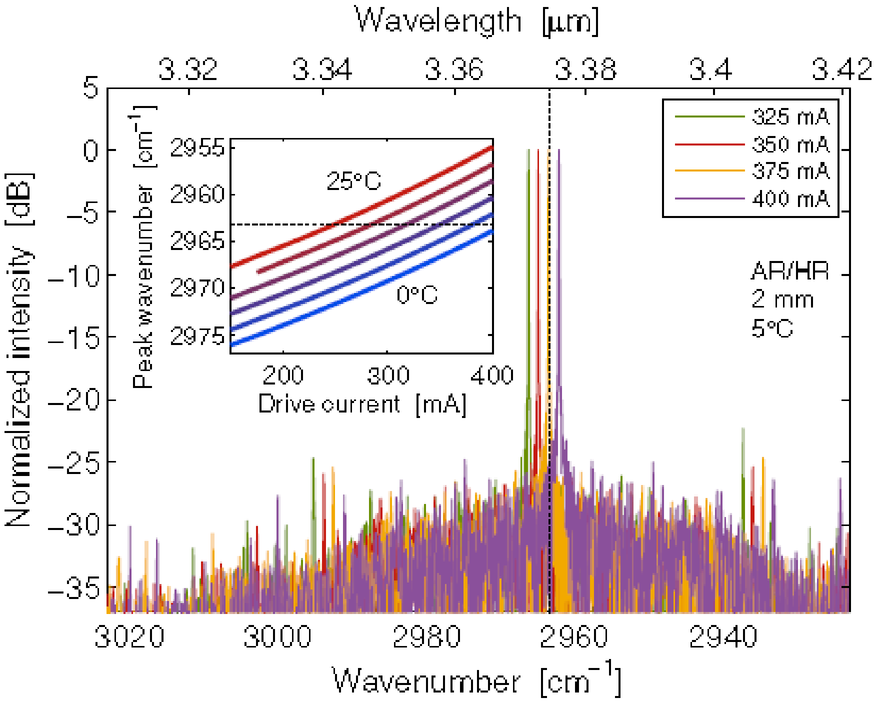
MORE JPL DFBs (METHANE WAVELENGTH)

[Borgentun et al., Opt. Expr. 23, 2446 (2015)]

Again employed NRL wafer material



L-I-V vs. temperature



Spectra vs. current & temperature

MORE ICL LIFETIME TESTING

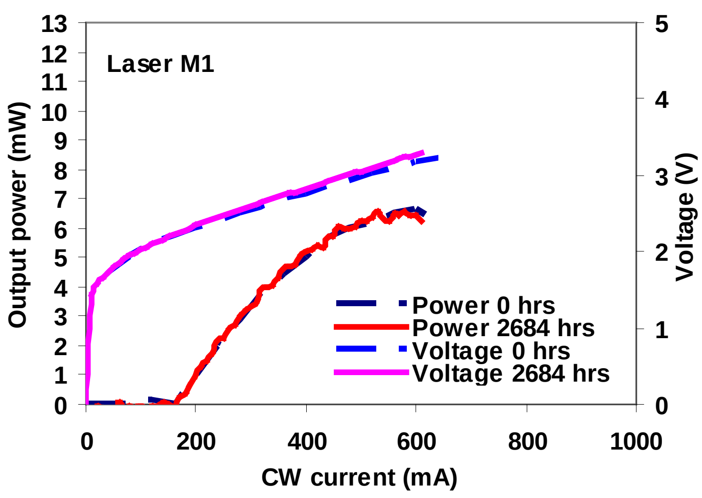
Besides JPL, CW lifetimes of NRL ICL ridges being measured by 2 industrial collaborators

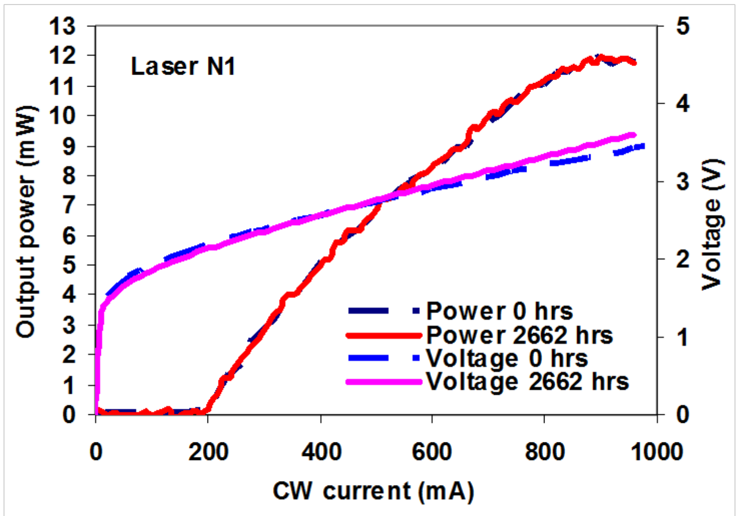
Company A:

1 device tested for 1000 hrs. @ RT, then 9000 hrs. @ *T* = 90 ºC – Negligible degradation implies lifetime > 100,000 hrs.

Another device tested 6000 hrs.

Devices showed slight *I-V* drift, but miniscule variation of cw output power





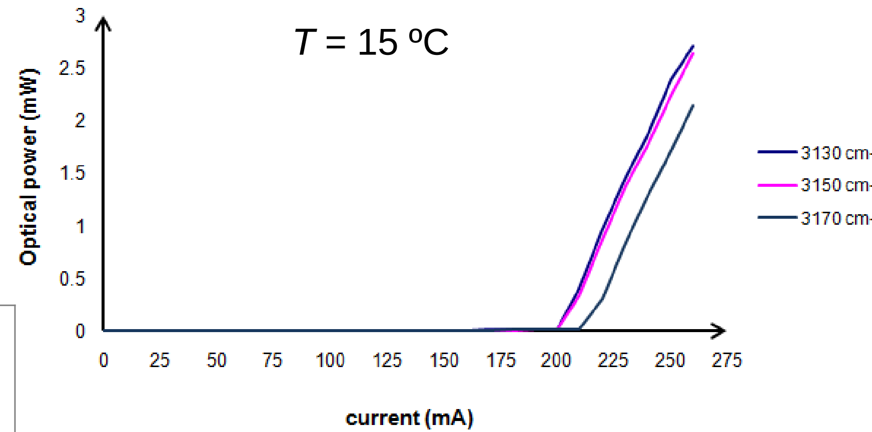
Company B: Tested 2 devices (λ = 4.7 μm) for 2600 hrs. @ *I* = 0.4 A & *T* = 20 ºC – Negligible degradation

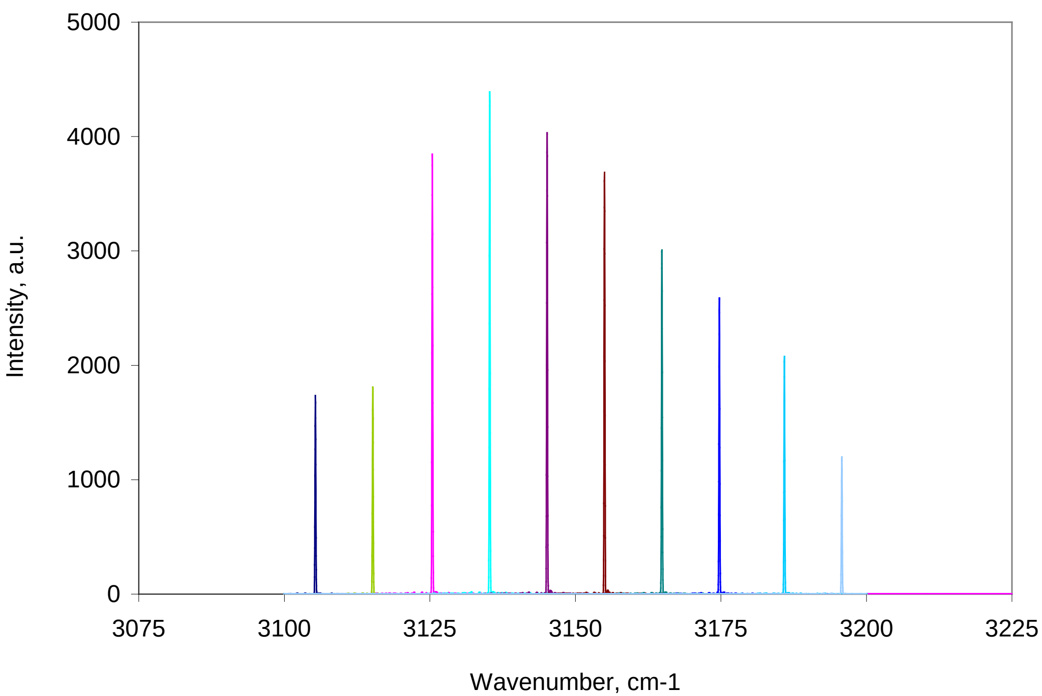
EXTERNAL CAVITY ICL

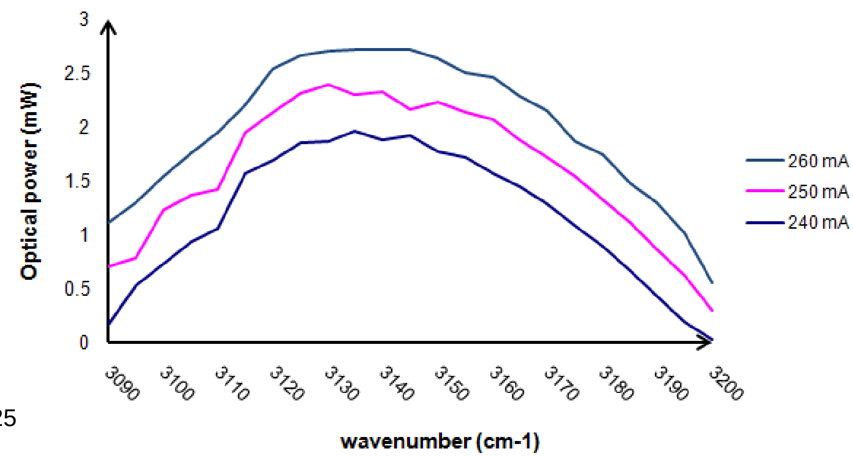
Caffey et al., Opt. Expr. 18, 15691 (2010)

With Daylight Solutions

- Narrow linewidth in EC-ICL configuration
- 105 nm tuning range
- > 1 mW cw @ all λ (Gen1)
- Low power consumption (< 1 W)

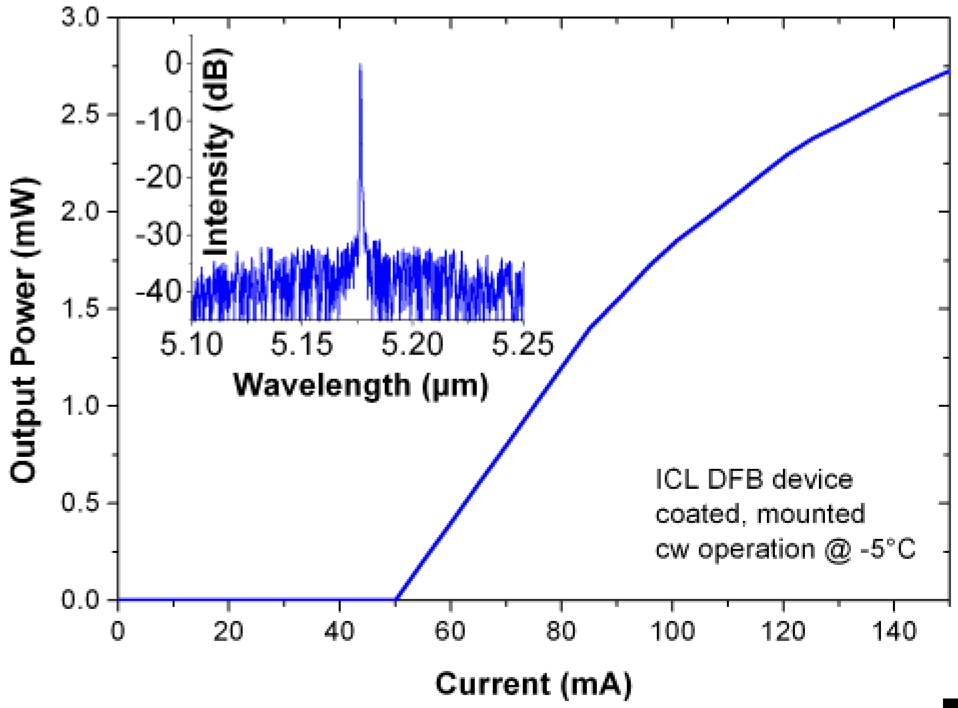






COMMERCIAL DFB ICLs

Since 2012, Maxion/ThorLabs & Nanoplus license NRL ICL patents



Nanoplus DFB: Drive power only 138 mW (> 10x lower than QCLs at λ = 5.2 μm)

[von Edlinger et al., PTL 26, 480 (2014)]

ICLs now incorporated into several commercial sensing products

MASS MEDIA PENETRATION!

On February 8, 2015, the German Vox Television Network news magazine *Auto Mobil* aired a 7-minute segment on a drive-by alcohol sensor developed by AirOptic (incorporating ICLs from Nanoplus)

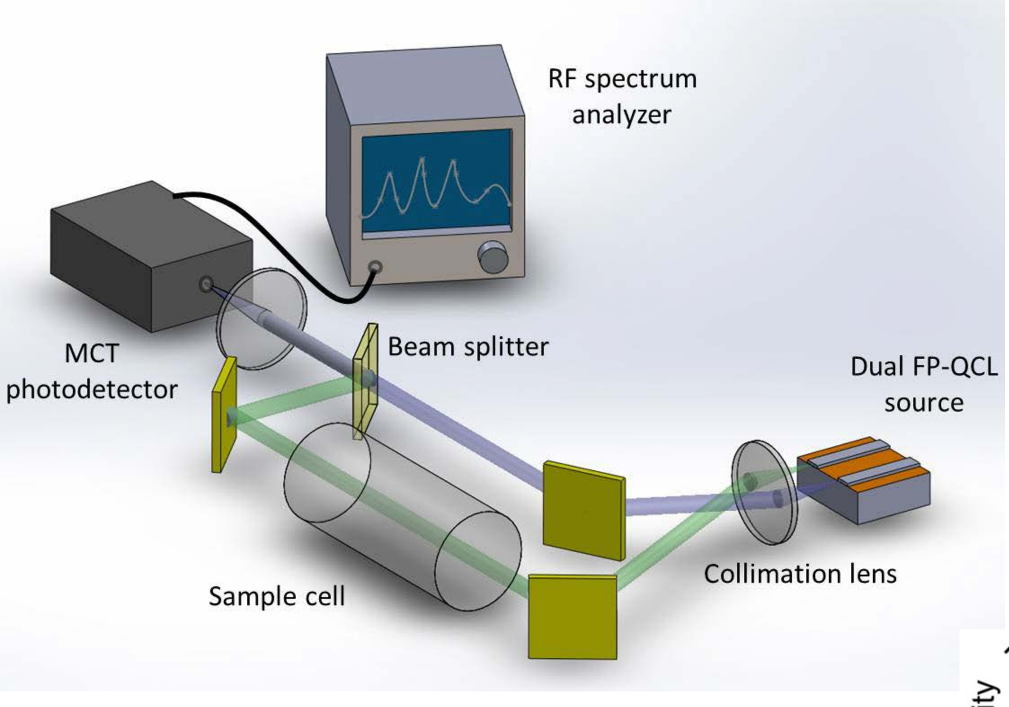
Next up: An ICL-based reality show…

ICLs for Multi-Heterodyne Spectroscopy

Collaboration with Gerard Wysocki group (Princeton U.)

- Princeton group recently demonstrated novel multi-heterodyne spectroscopy technique using QCLs
  - Successful sensing of N_2O, NH_3, *etc.*
- Objective is high-resolution mid-IR sensing
  - No FTIR required
  - Employs matched pairs of mid-IR Fabry-Perot lasers (Broader bandwidth & less expensive than DFBs)
- *This collaboration:* Extend to ICLs, for expanded spectral coverage, low drive power budget, small spatial footprint
- All experiments performed at Princeton U., using narrow-ridge FP ICLs supplied by NRL

Multi-Heterodyne Spectroscopy Set-Up



- **Two conventional FP lasers** *[L. Diehl et al., APL 88, 201115 (2006)]*
- **Same gain material – But different ridge-widths provide different I_{th} & FSR**
- **1 GHz MCT photodetector**

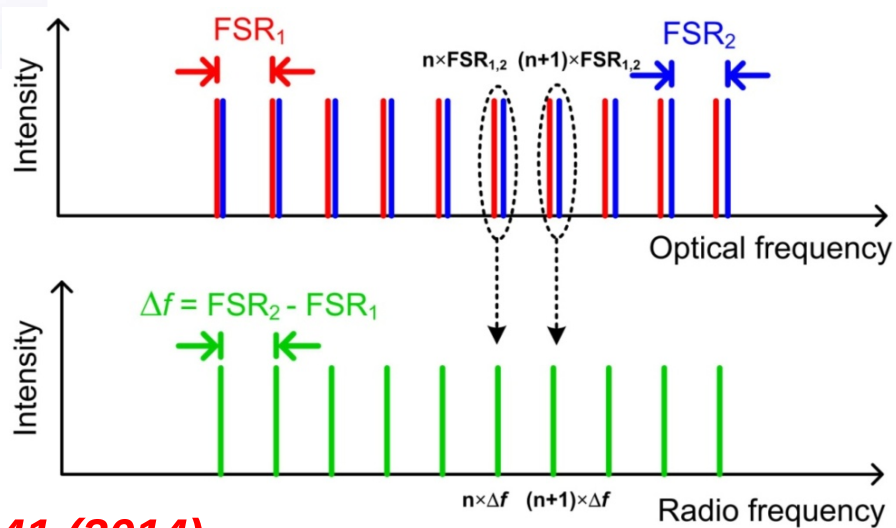
$$I \propto \left| \vec{E}_s e^{i(\omega_s t + \varphi_s)} + \vec{E}_{LO} e^{i((\omega_s + \Omega)t + \varphi_{LO})} \right|^2$$

$$= \left|\vec{E}_s\right|^2 + \left|\vec{E}_{LO}\right|^2 + 2\vec{E}_s \cdot \vec{E}_{LO} \cos[\Omega t + (\varphi_s - \varphi_{LO})]$$

Phase info.

Amplitude (absorption)

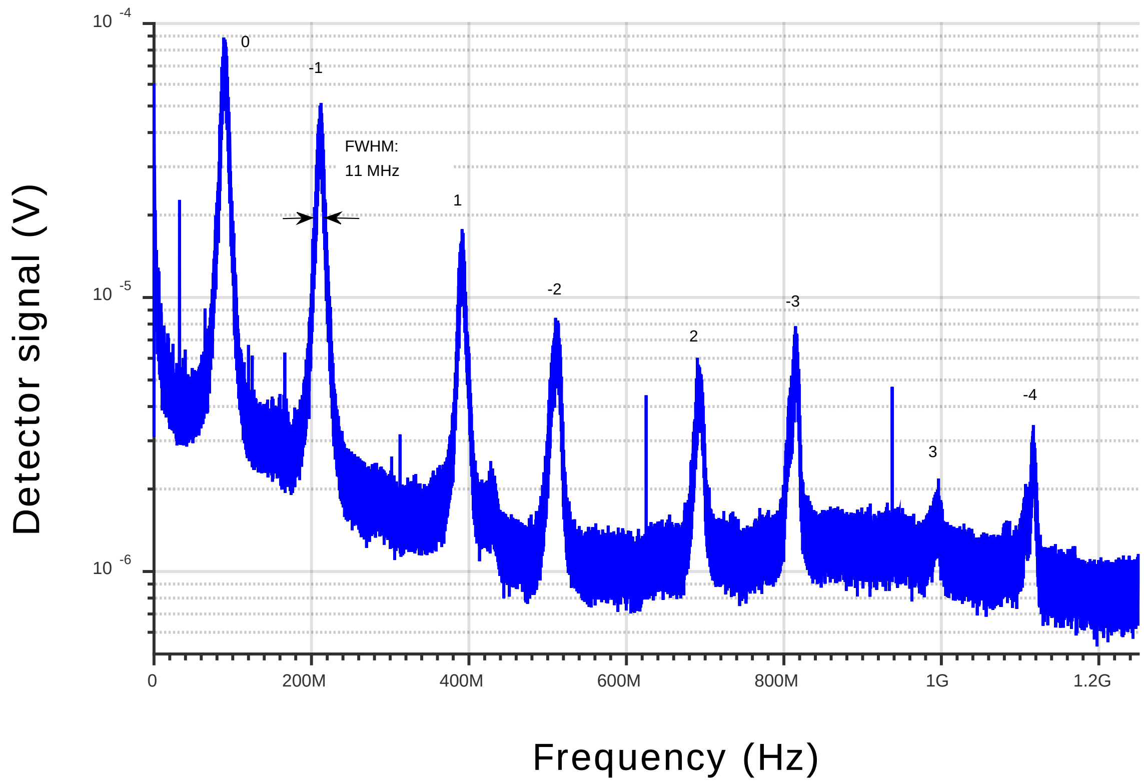
RF freq.



Y. Wang, G. Wysocki, et al., APL 104, 0311141 (2014)

Preliminary ICL Multi-Heterodyne Spectra

Beatnote spectrum: **Combined outputs from 2 narrow-ridge FP ICLs ($\lambda \approx 3.6\ \mu m$):**



- ICL cavity lengths intentionally mismatched (FSR too small for sister cavities)
- FWHM Linewidth = 11 MHz (Limited by spectral jitter)
- Greater spectral resolution attainable by increasing cavity length (Shorter FSR)
- *Next step:* Apply to gas sensing

MULTI-MODE ABSORPTION SPECTROSCOPY (MUMAS)

Collaboration with Paul Ewart group (Oxford U.)

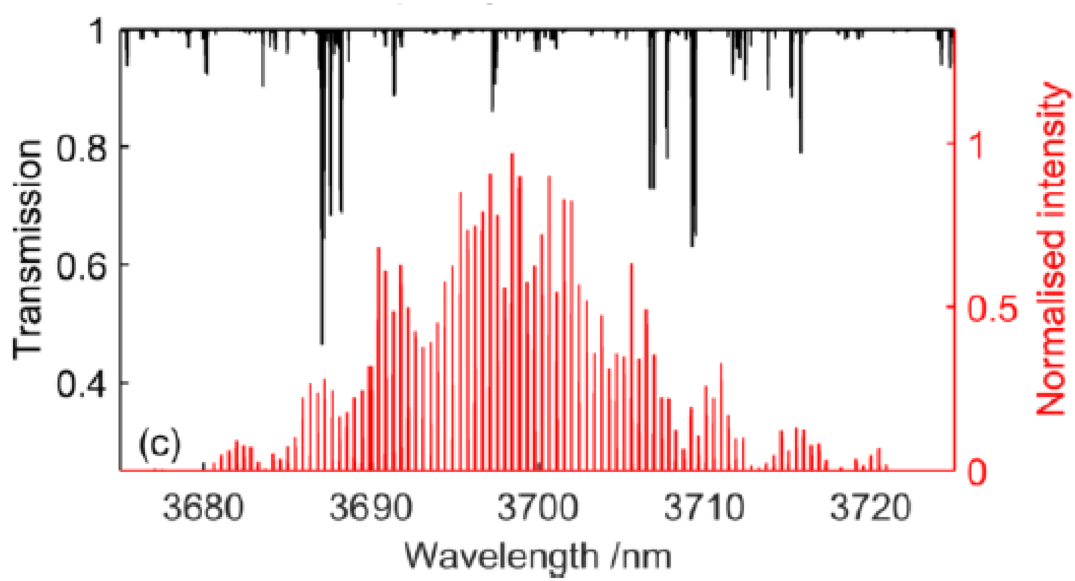
- Oxford group recently developed & demonstrated MUMAS spectroscopy
  - Scan (with current) laser spectral output across one longitudinal-mode spacing – Observe transmission dip every time any laser mode crosses a molecular absorption line
  - Model response to a given molecule by combining known laser emission spectrum with known Hi-Tran (or other) molecular absorption spectrum
  - Broad spectral range of multi-mode ridge laser suitable for simultaneous detection of multiple gas species
- Objective is simple, robust, inexpensive sensing system – Requires only a single, multi-mode laser
- Previously applied to visible & near-IR, using standard diodes & diode-pumped Er:Yb:glass; also mid-IR using DFG (with inconveniently-slow scan rate)
- *This collaboration:* ICL source for faster, simpler, & less expensive mid-IR system
- All experiments performed at Oxford, using narrow-ridge FP ICLs supplied by NRL

MUMAS APPLICATION TO CH_4

[Northern et al., submitted to Opt. Lett.]

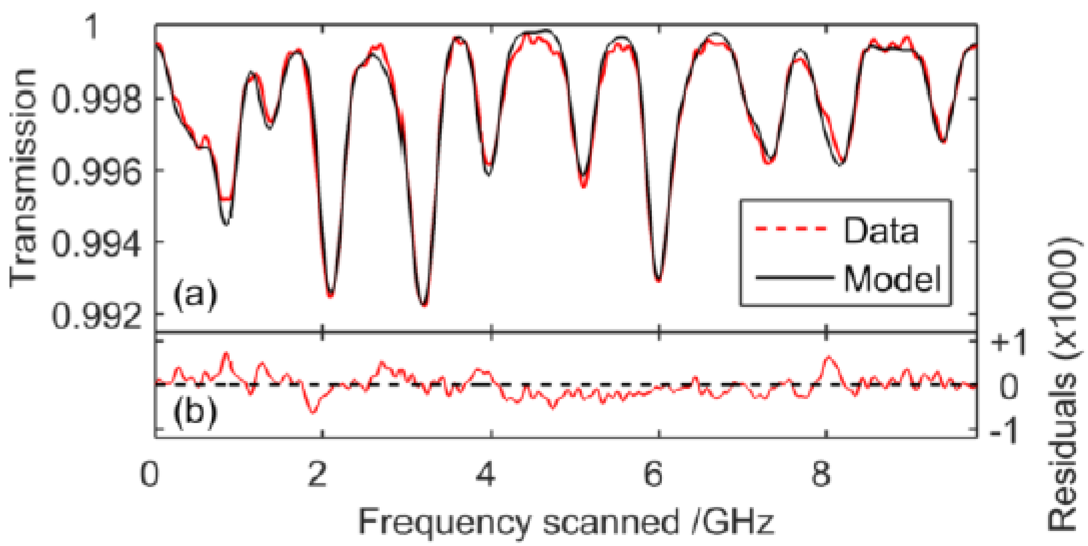
CH_4 absorption spectrum

Laser emission spectrum (showing multiple longitudinal modes)



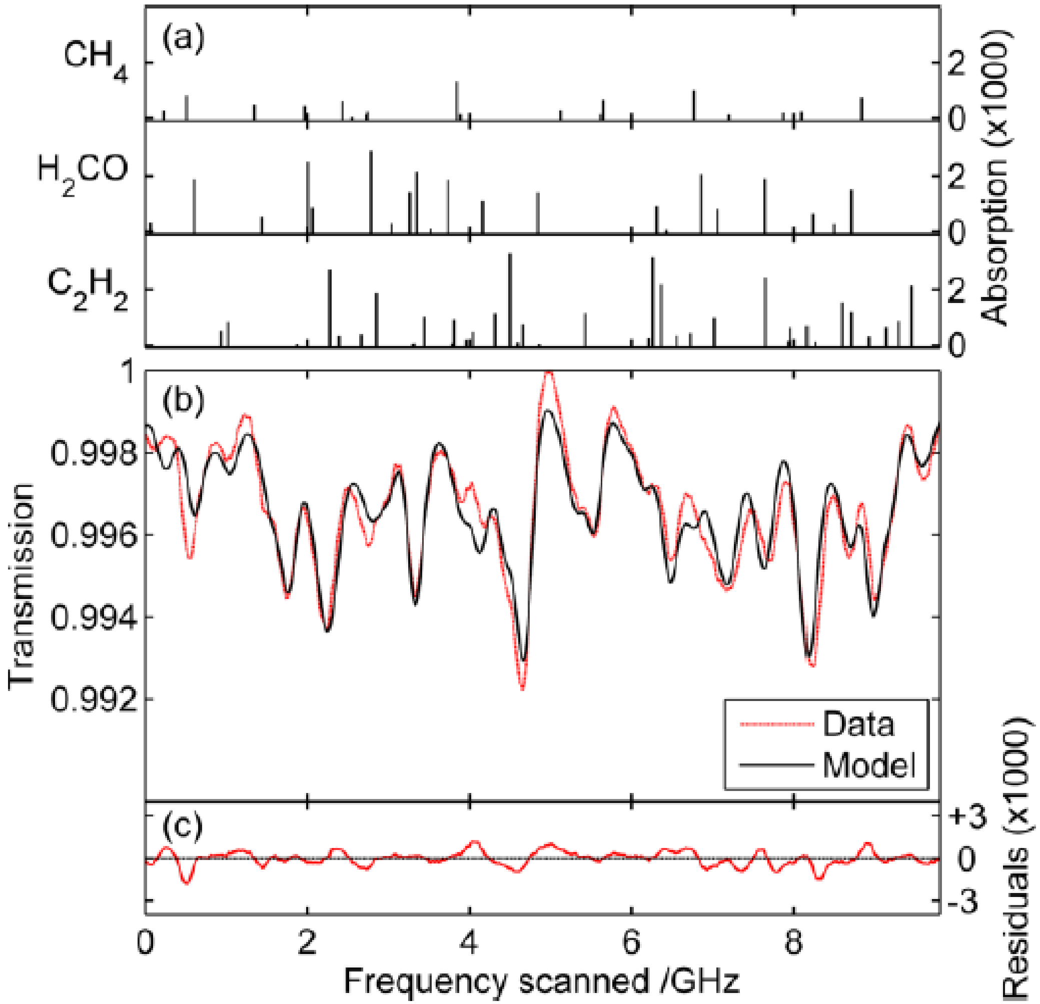
Modeled & measured transmission spectra

Residuals



SIMULTANEOUS DETECTION OF 3 SPECIES

[Northern et al., submitted to Opt. Lett.]

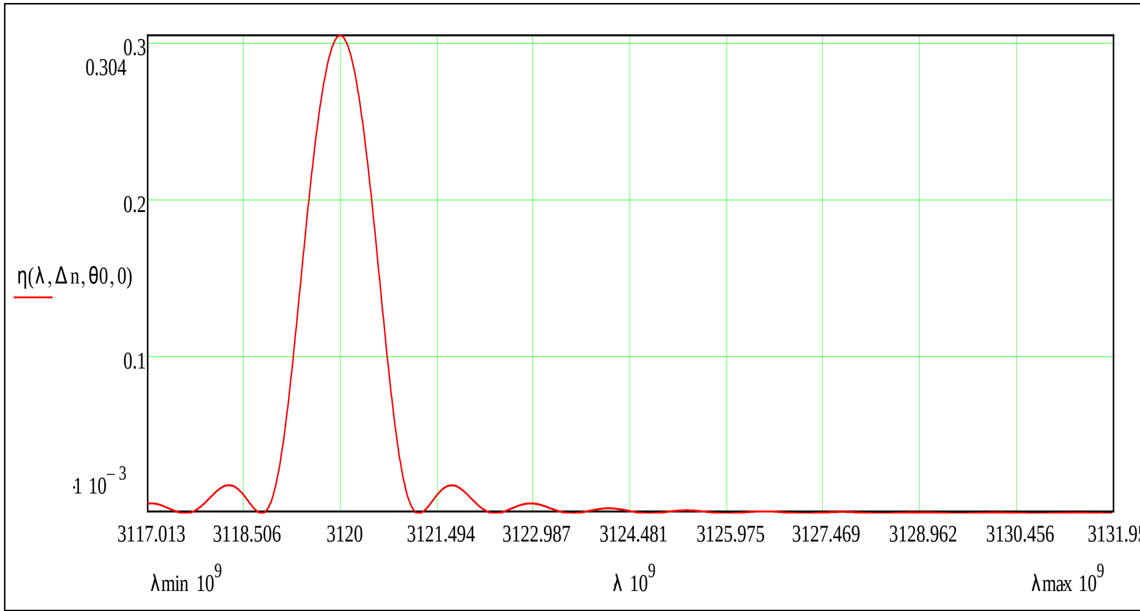


Detected concentrations of 0.86 mbar for CH_4 & 2.2 mbar for C_2H_2 agree well with actual values of 1.2 & 1.6 – Actual H_2CO (from vapor above water/methanol solution) concentration insufficiently calibrated to compare (0.1 mbar detected)

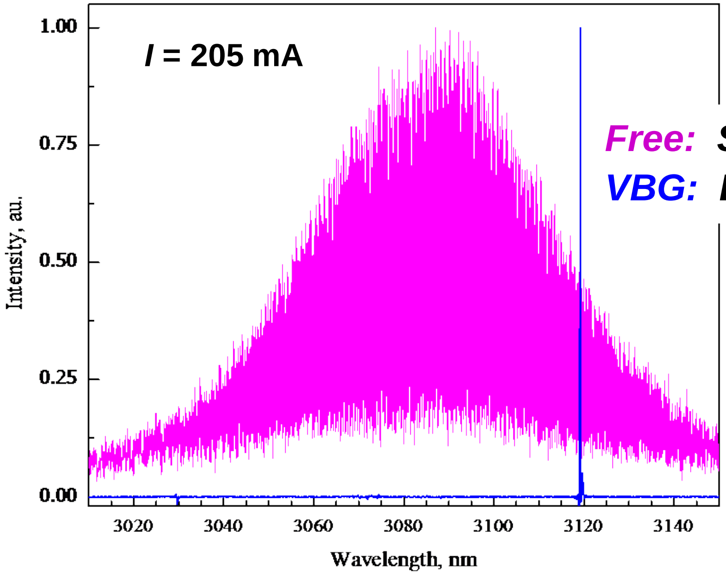
VOLUME BRAGG GRATING CAVITY ICL

Collaboration with Leonid Glebov group (CREOL)

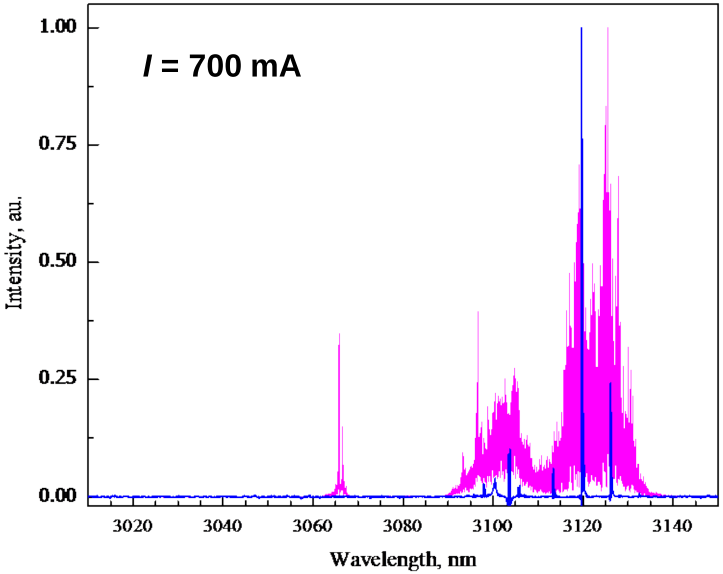
- External cavity with volume Bragg grating (VBG) mirror substantially narrows laser linewidth & enhances spectral/spatial brightness
- PTR glass employed in visible & near-IR absorbs at $\lambda \geq 2.8\ \mu m$ (& much more strongly @ $\lambda \geq 4\ \mu m$) – Transparent glasses for mid-IR now under development
- Nonetheless, investigate whether VBG feedback sufficient for external-cavity ICL (with high gain) operating at $\lambda \approx 3.1\ \mu m$
- *Simulation:* VBG diffraction efficiency ≈ 30% & spectral linewidth ≈ 1.2 nm (both degraded by Fresnel reflection from uncoated VBG surface)
- All experiments performed at CREOL, using FP ICLs (18 μm x 4.5 mm, HR/AR-coated) supplied by NRL



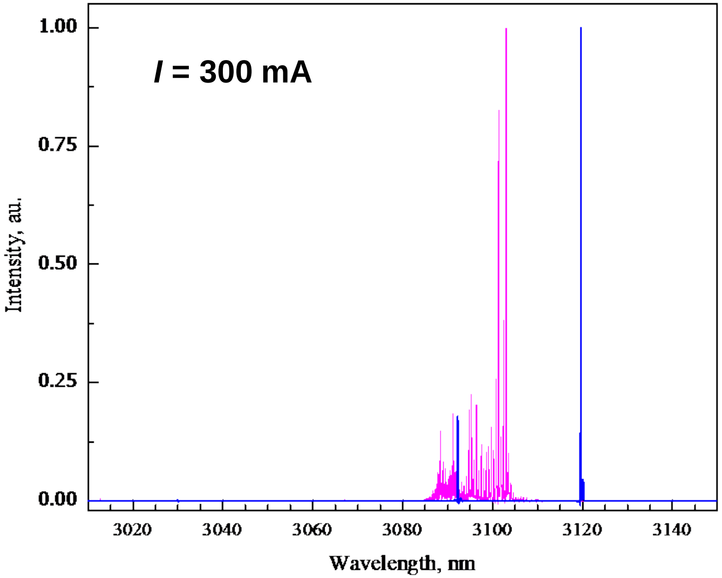
ICL VBG – SPECTRA



Free: *Still ASE ($I < I_{th}$)*
VBG: *Lasing in narrow line*

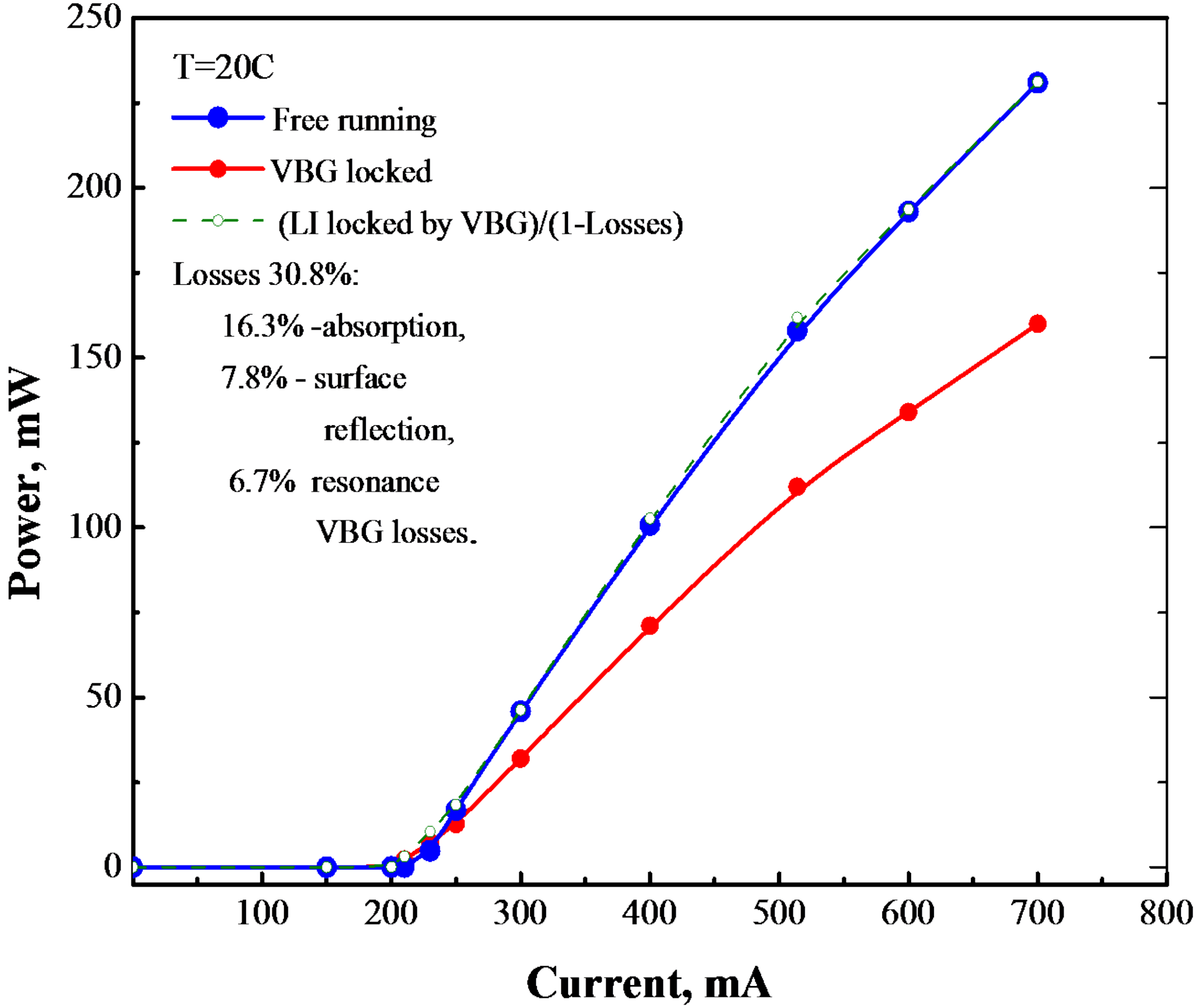


Free: *Continues to broaden*
VBG: *More parasitic lines emerge*



Free: *Broad multi-mode*
VBG: *2^{nd} line appears (FP at uncoated VBG surface?)*

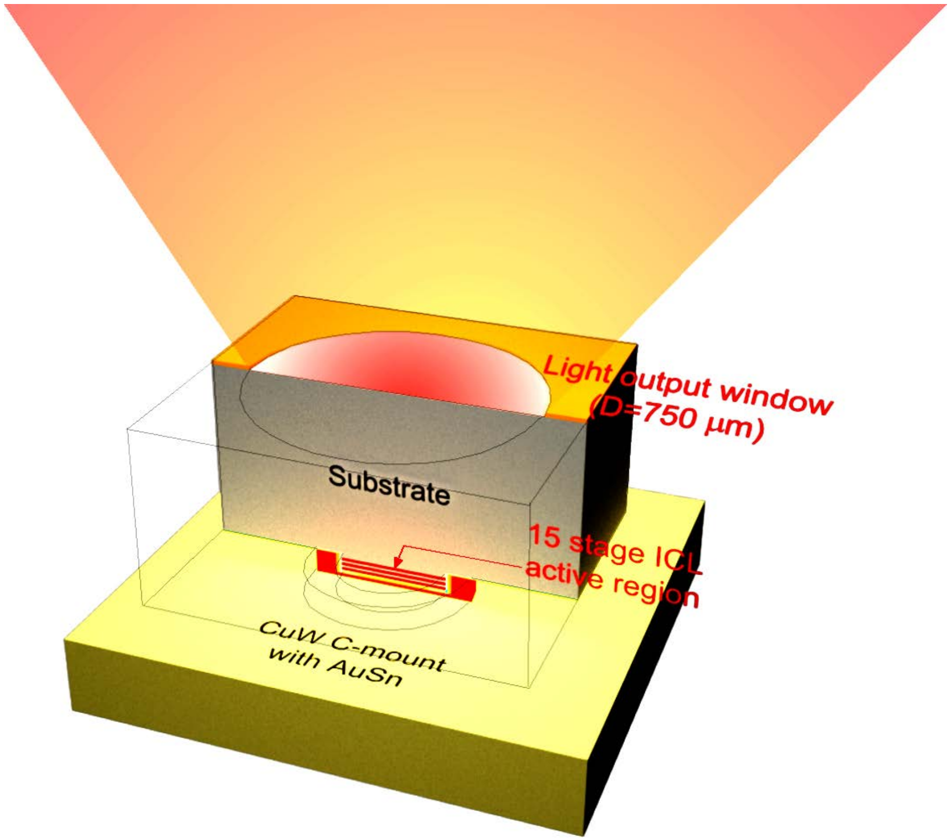
VBG: L-I CHARACTERISTICS

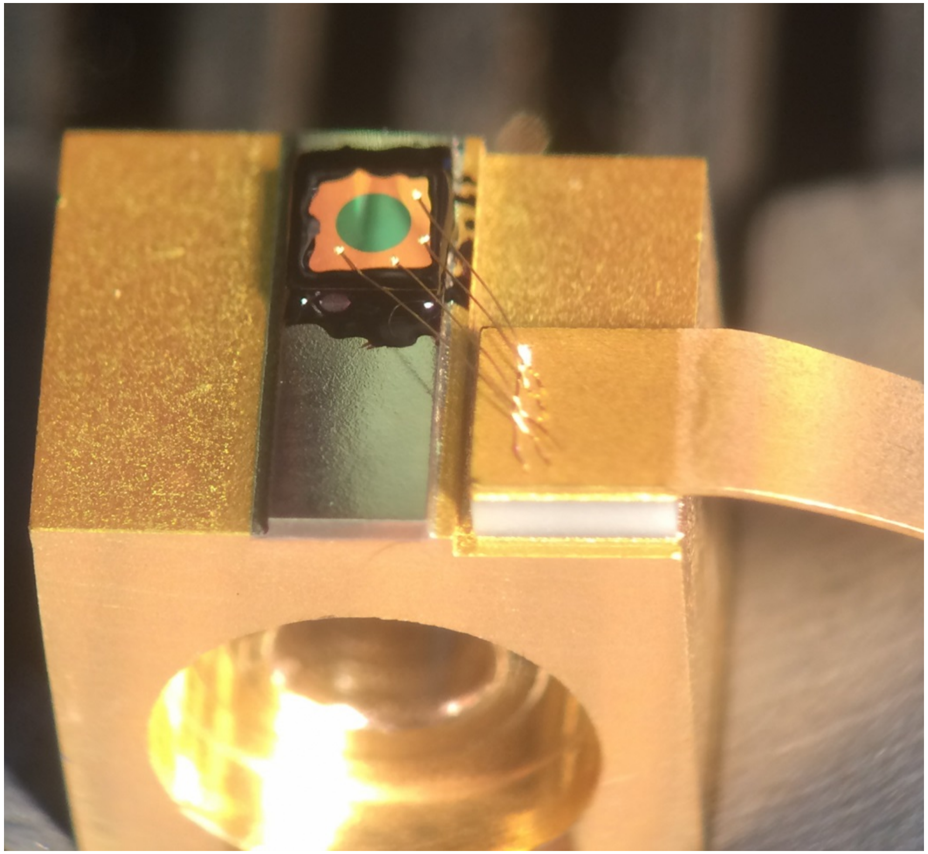


VBG line narrowing incurs relatively modest power sacrifice

ALTERNATIVE IR SENSING SOURCE: IC LEDs

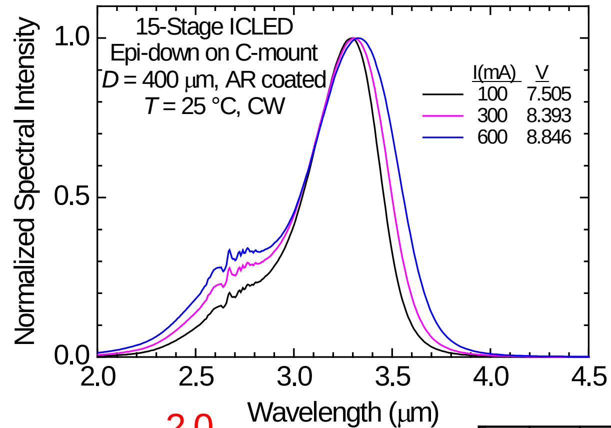
Single attempt, with no optimization or measures to enhance out-coupling efficiency (beyond AR coating on output surface)

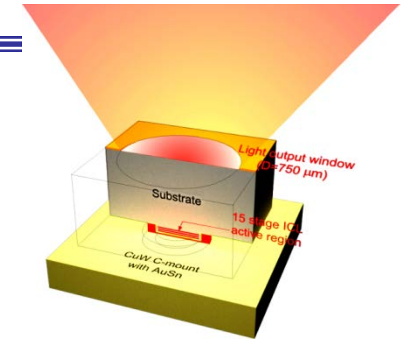


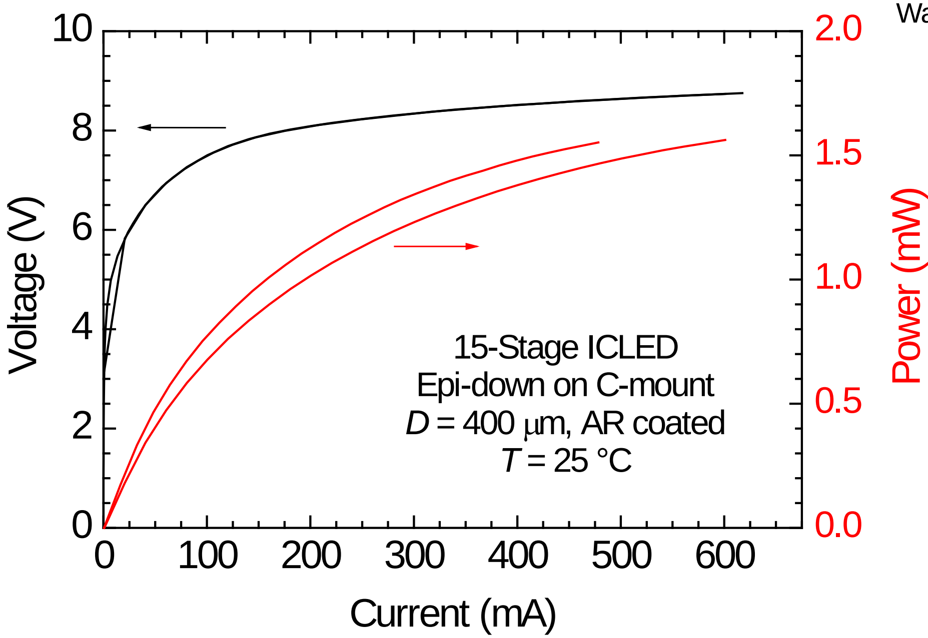


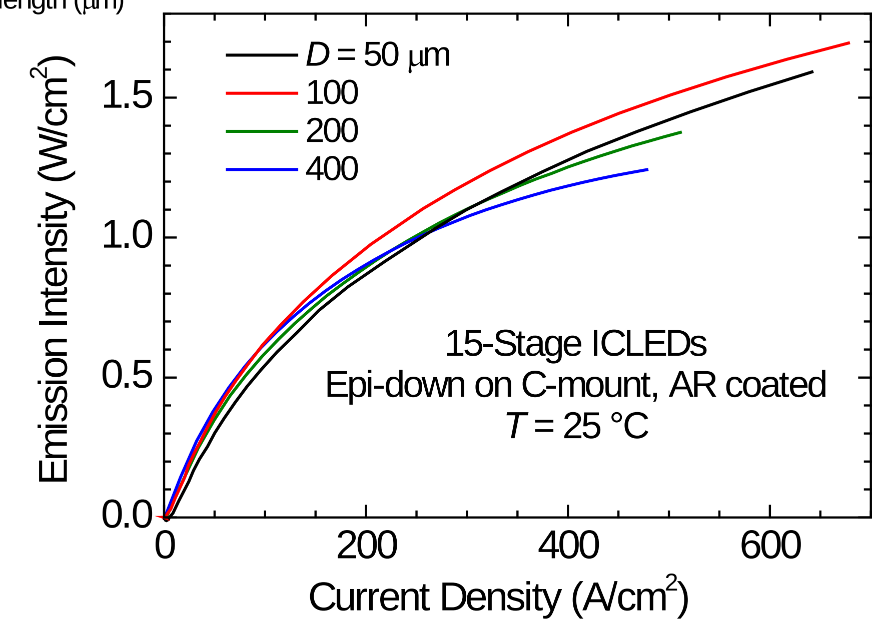
ICLEDs: INITIAL PERFORMANCE RESULTS

Abell et al., APL 104, 261103 (2014)





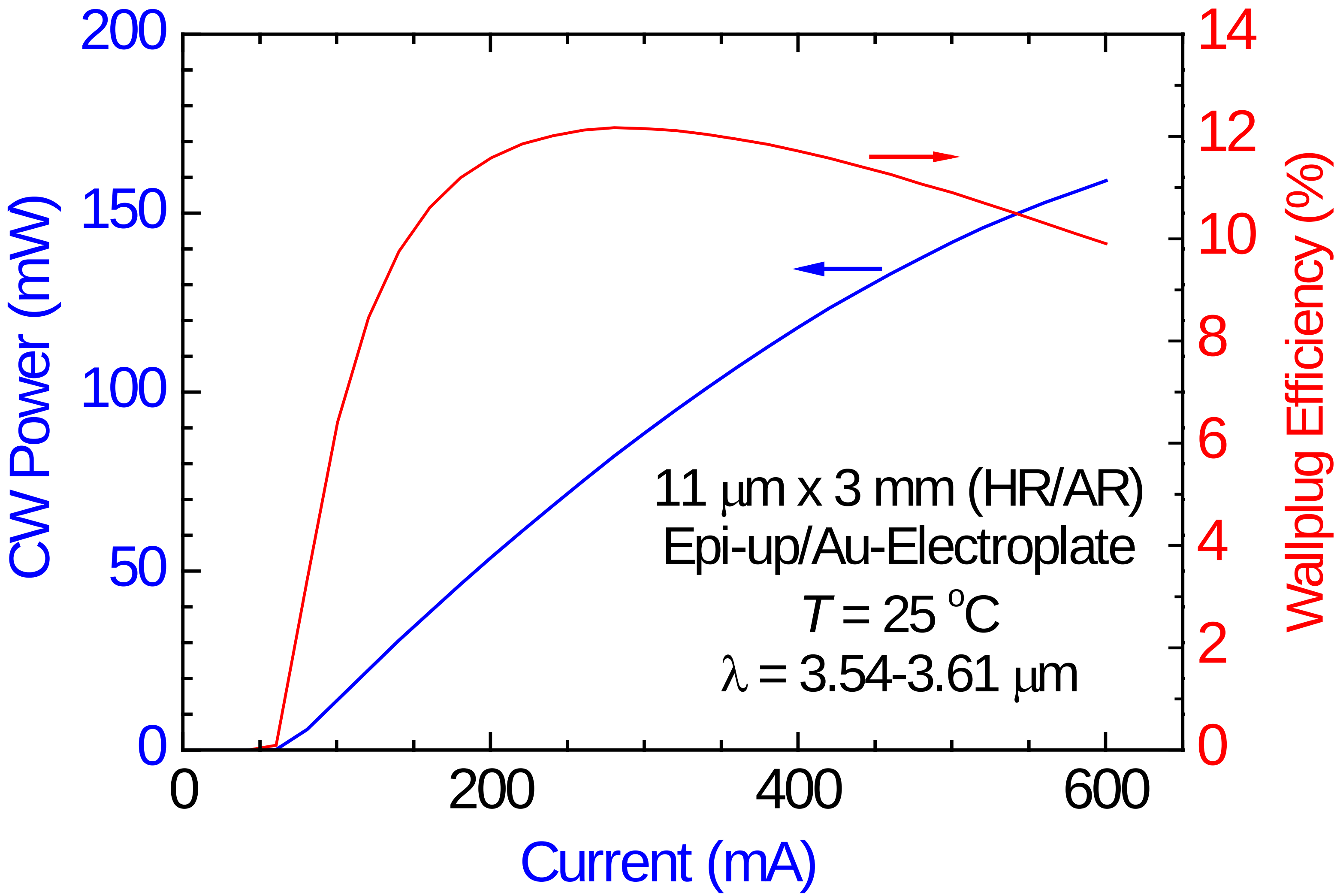




P_{out}^{cw} = 1.6 mW – Record for mid-IR LED (Highest commercial ≈ 200 µW)

Emission intensity 5x any previous report

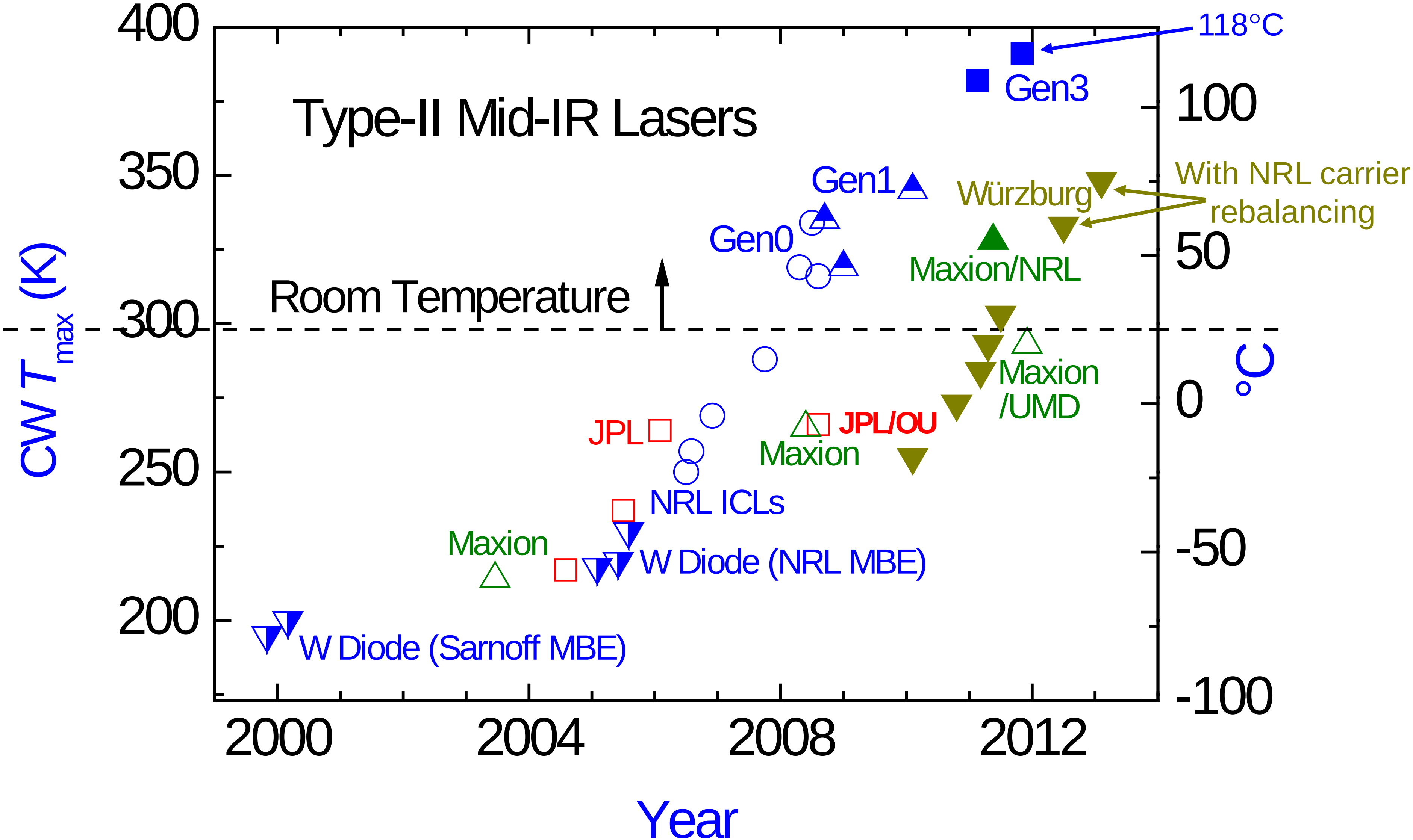
Gen3: HIGHER CW POWER & WPE (2011)



P_{max}^{cw} (25 °C) = 159 mW ($M^2 \approx 3$); WPE = 9.9% @ P_{max}

EPI-DOWN MOUNTING: HIGHER T_{max}^{cw}

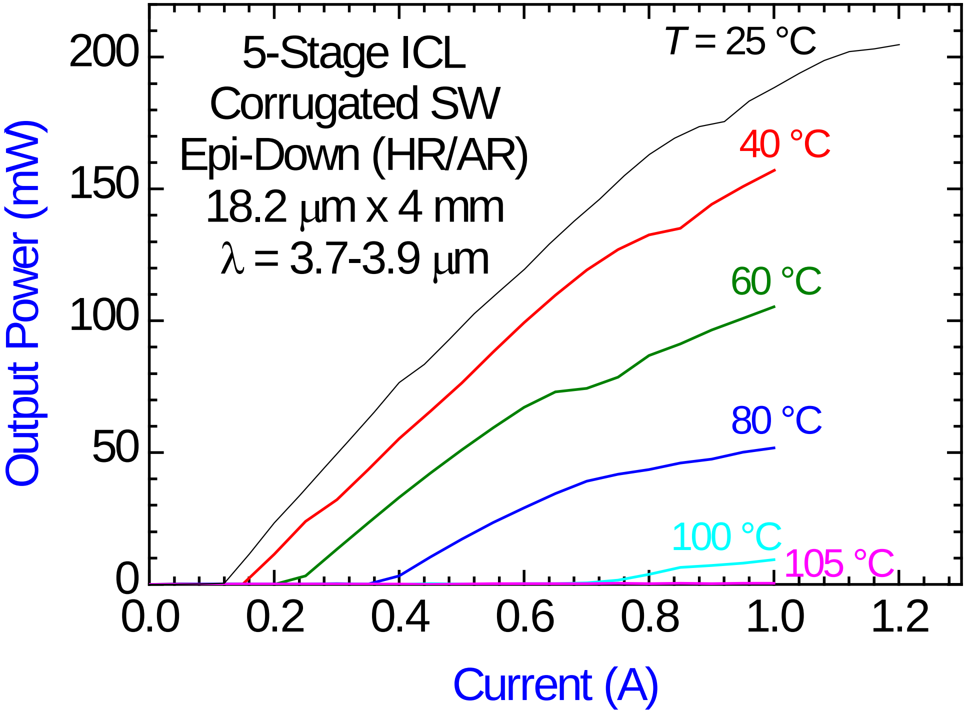
[Bewley et al., Opt. Expr. 20, 20894 (2012); U.S. Patent #8,879,593 (2014)]

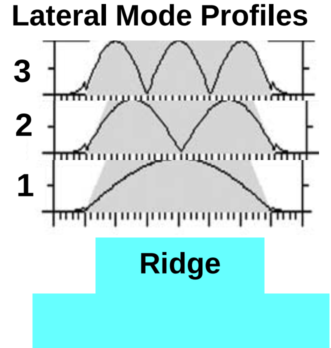


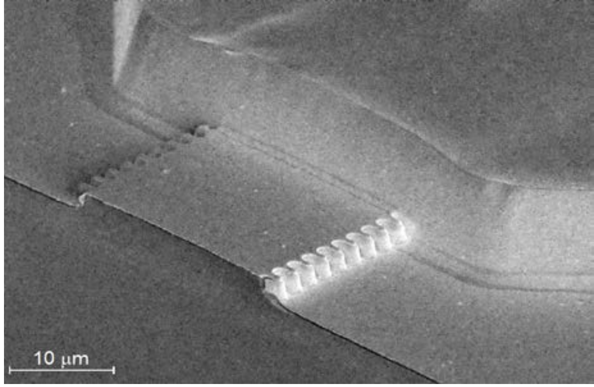
Also WPE = 14.6%

CORRUGATED-SIDEWALL ICLs

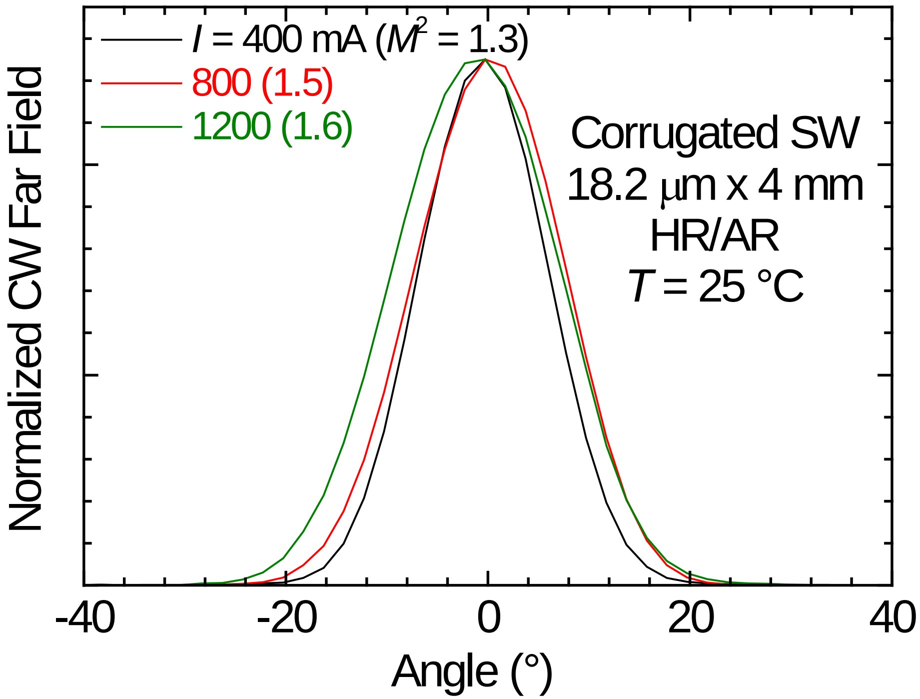
[Bewley et al., Opt. Expr. 20, 20894 (2012)]







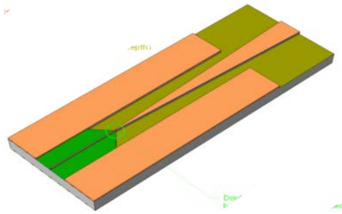
Suppress higher-order modes for better beam quality



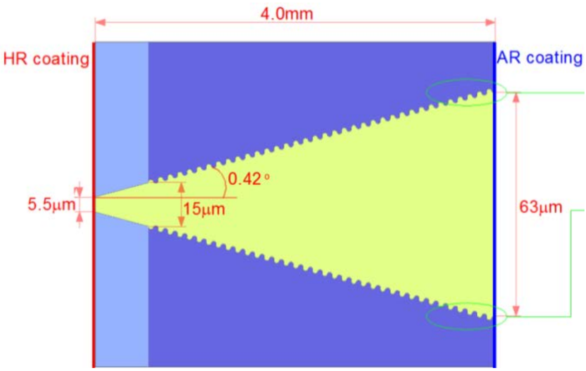
P_{max}^{cw} > 200 mW @ T = 25 ºC (M^2 = 1.6)

***Wider ridge (25.1 μm)*: 305 mW (M^2 = 2.2); WPE = 6.6% @ P_{max}**

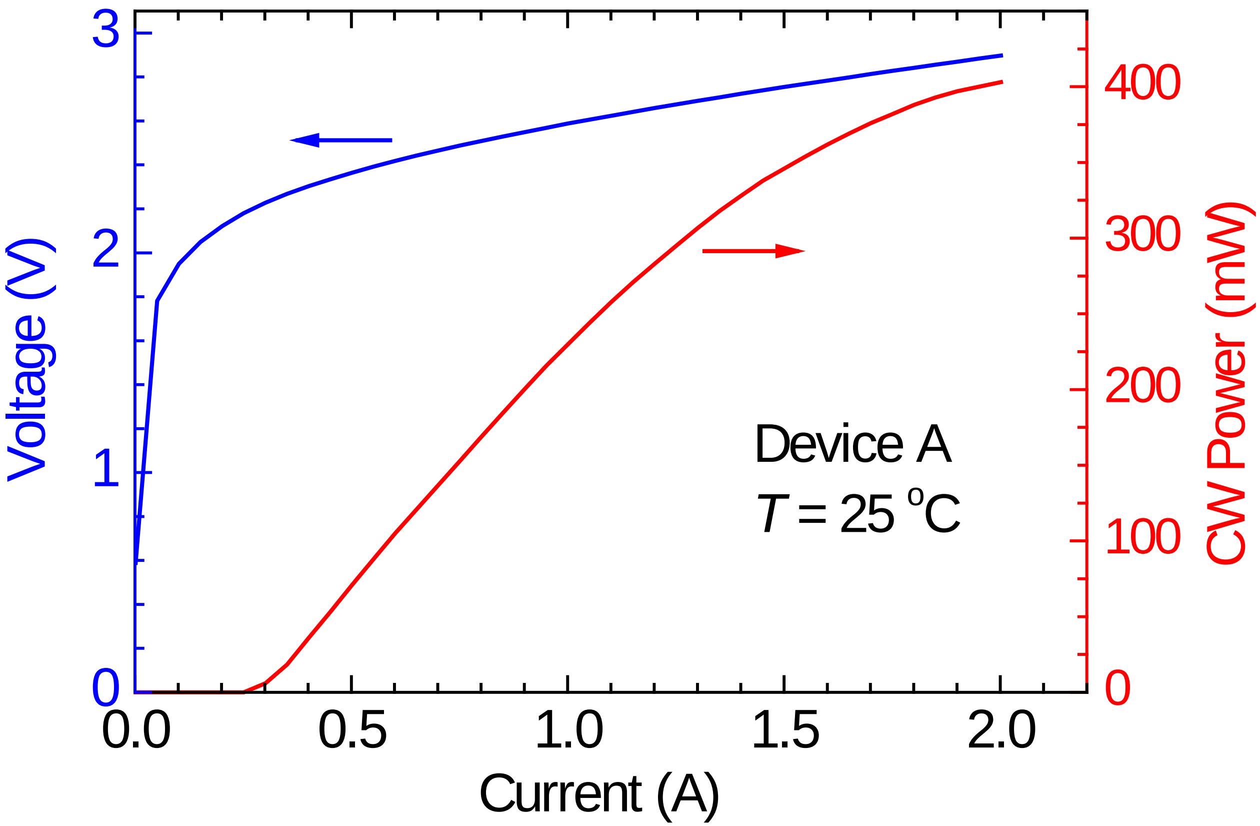
TAPERED ICLs

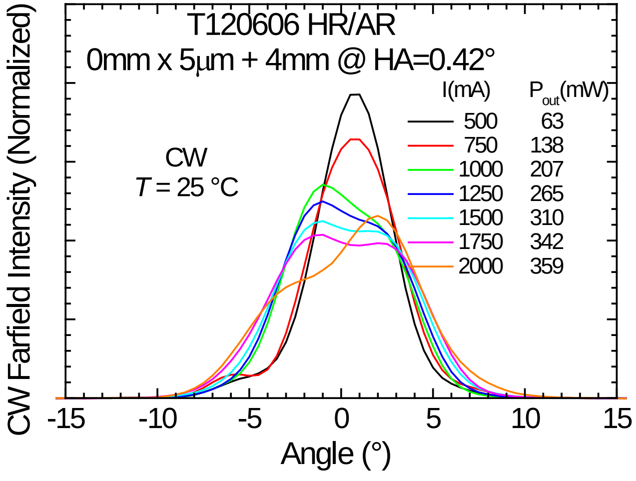


[Bewley et al., APL 103, 111111 (2013)]



Tapered ridge with no straight section

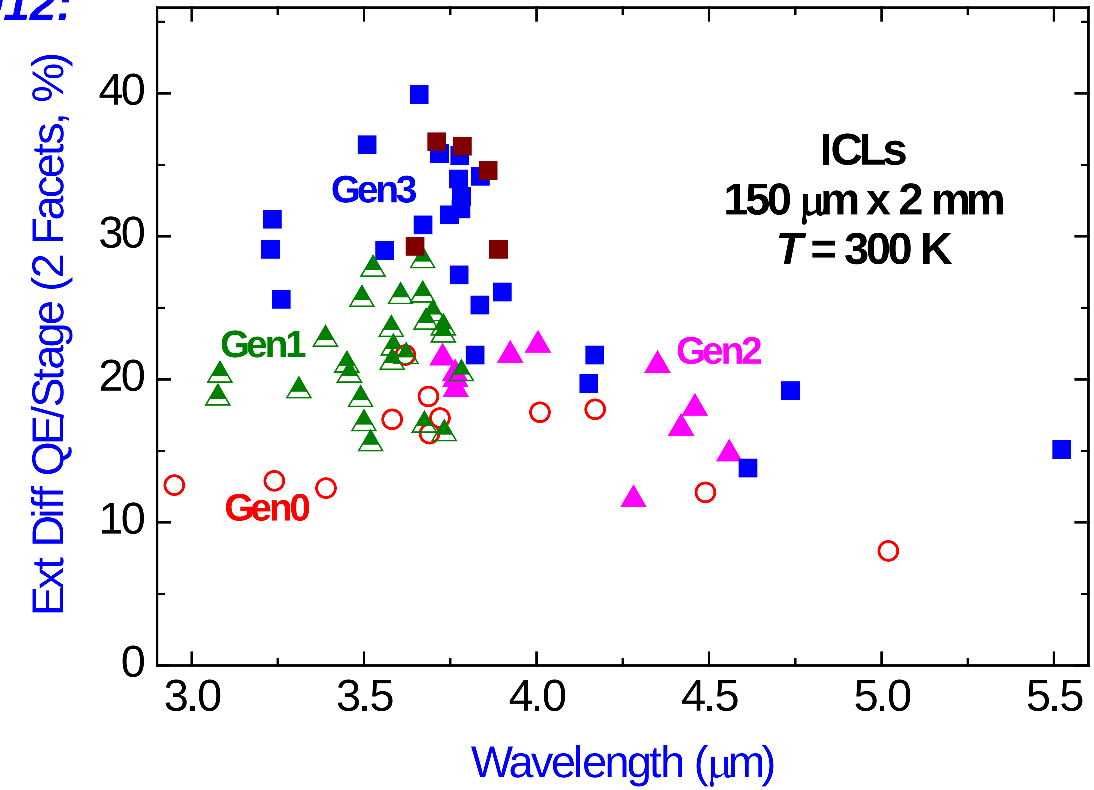




P_{max}^{cw} (25 ºC) = 403 mW (M^2 = 2.3), WPE = 7.0% @ P_{max}

TO FURTHER ENHANCE POWER & BRIGHTNESS: INCREASE EFFICIENCY

As of October 2012:

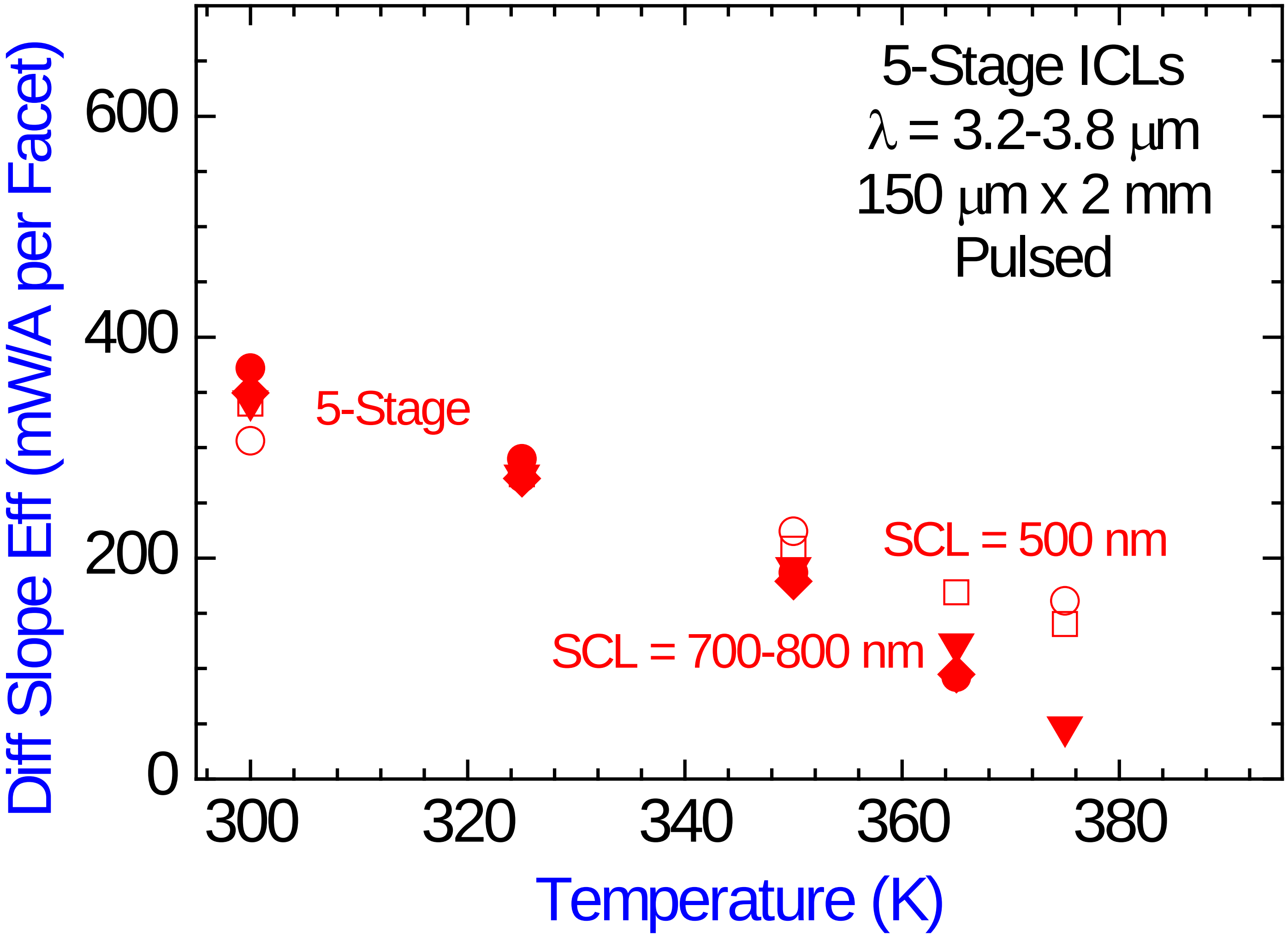


Try varying other parameters in rich ICL design space, *e.g.*:

- Thicker *n*-GaSb separate confinement layers (SCLs), for lower mode overlap with active & clad, hence reduced loss

- More active stages (*e.g.*, 7 *vs.* 5), for higher slope efficiency & gain

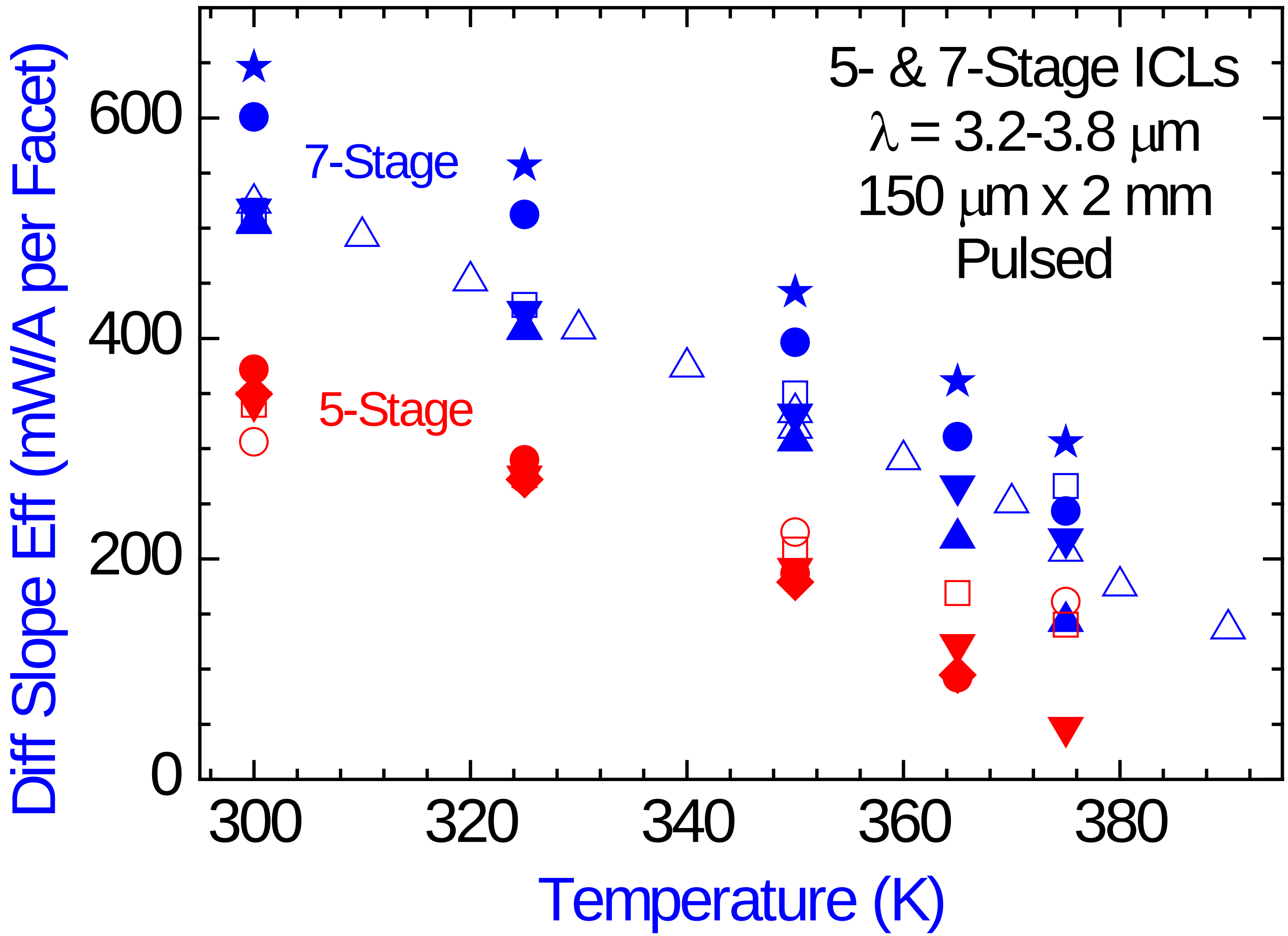
5 STAGES WITH THICKER SCLs



Thick SCLs increase efficiency at 300 K, but fail to provide enough gain at high T

7 STAGES

[Bewley et al., Opt. Expr. 22, 7702 (2014)]

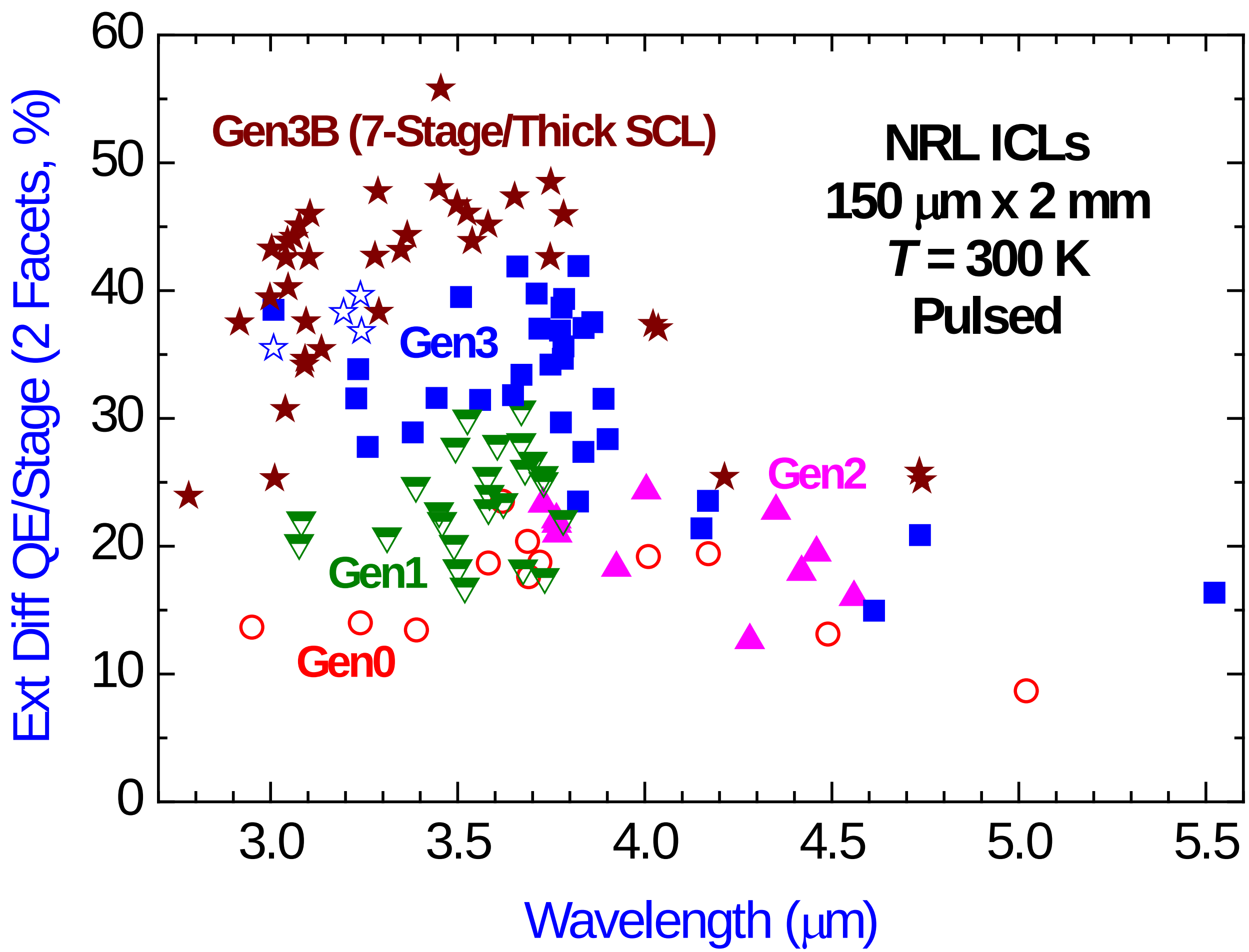


Thick SCLs increase advantage at 300 K, while retaining sufficient gain at high T

Even better news: Slope$_7$/Slope$_5$ > 7/5 indicates lower loss!

IMPROVED EDQE

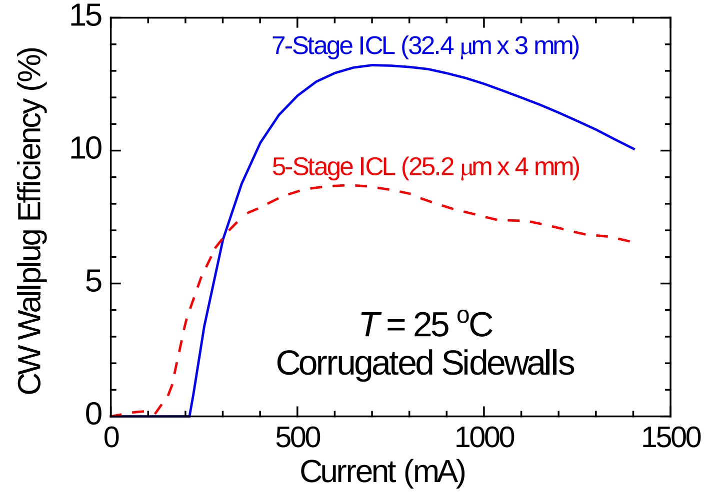
Result is significantly higher EDQE:

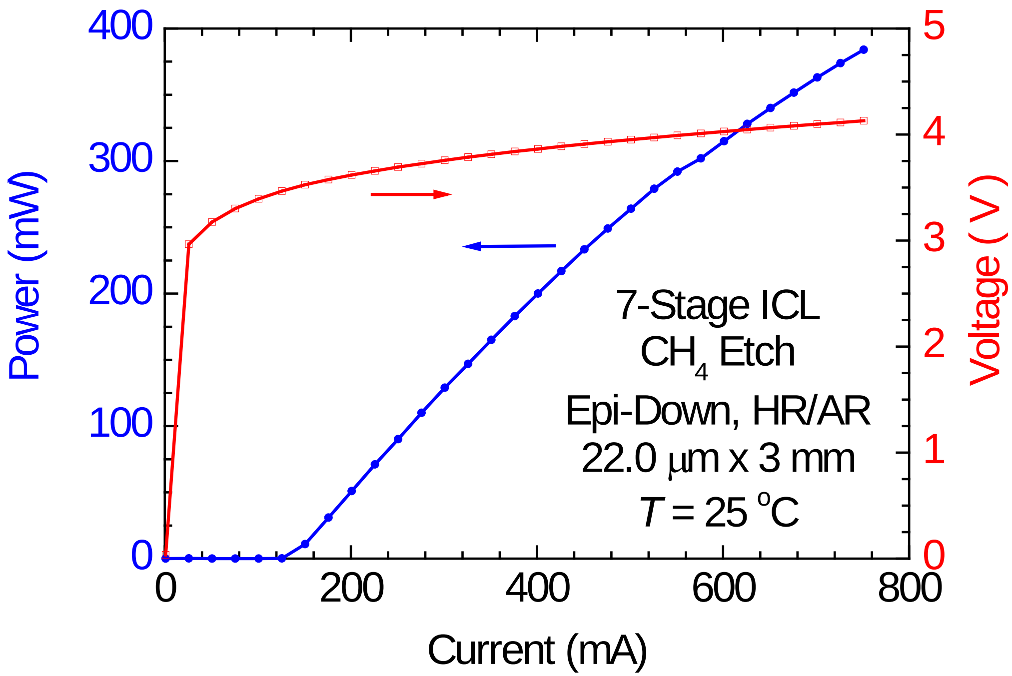


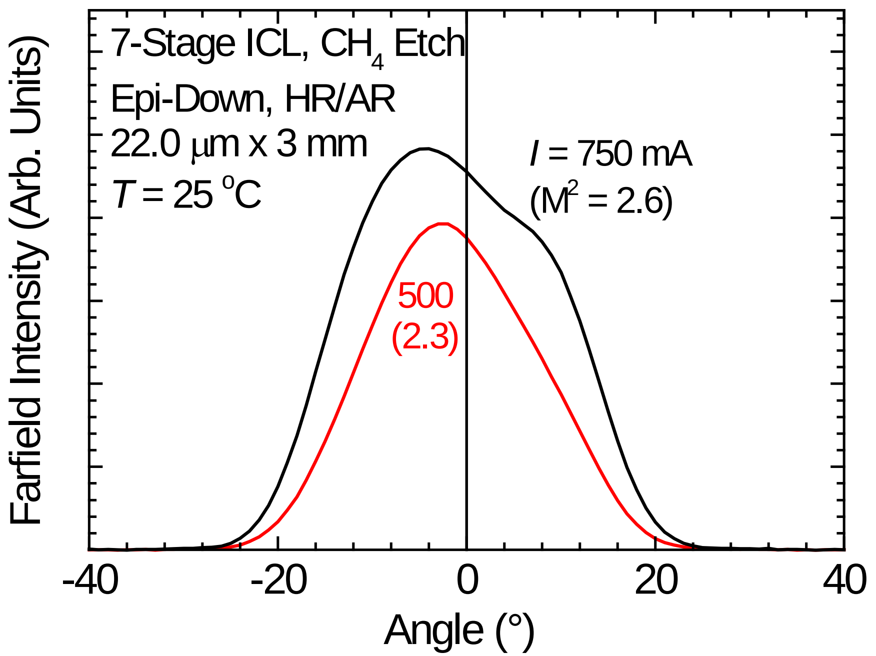
7-stage ICLs with thick SCLs (Gen3B) exhibit higher EDQE & lower loss at all λ

7-STAGE NARROW RIDGES

[Canedy et al., Opt. Expr. 22, 7702 (2014)]





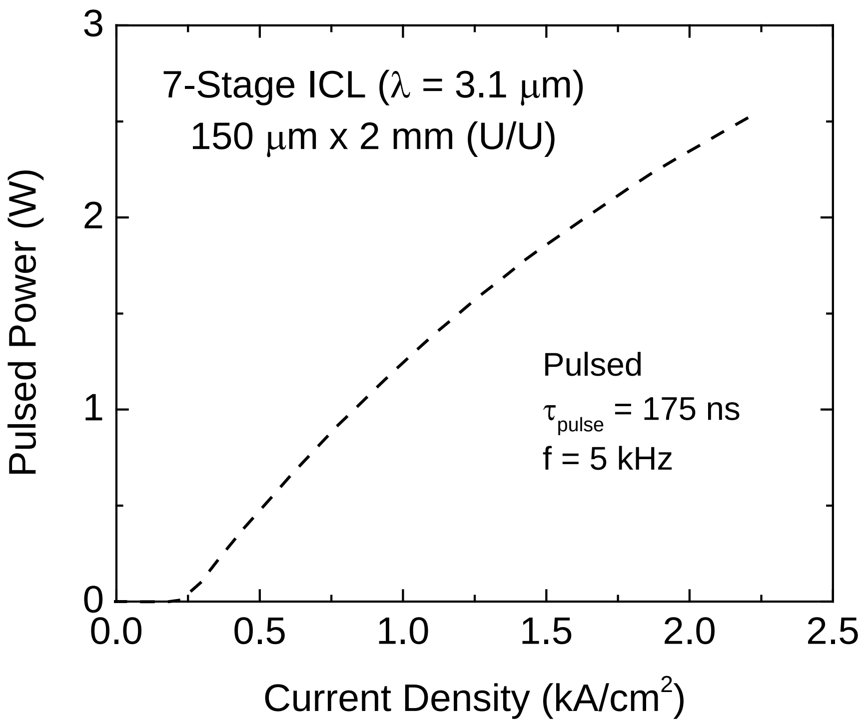


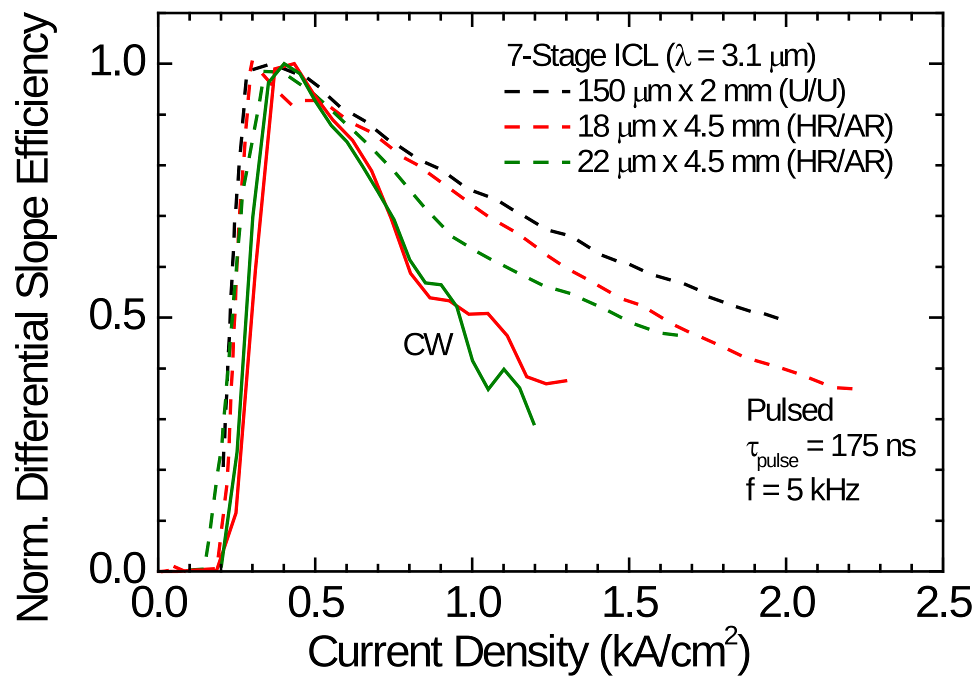
P_{max}^{cw} = 384 mW in high-quality beam (M^2 = 2.6)

WPE = 12.4%

BUT P_{max} LIMITED BY EFFICIENCY DROOP

[Merritt et al., submitted to Appl. Opt.]





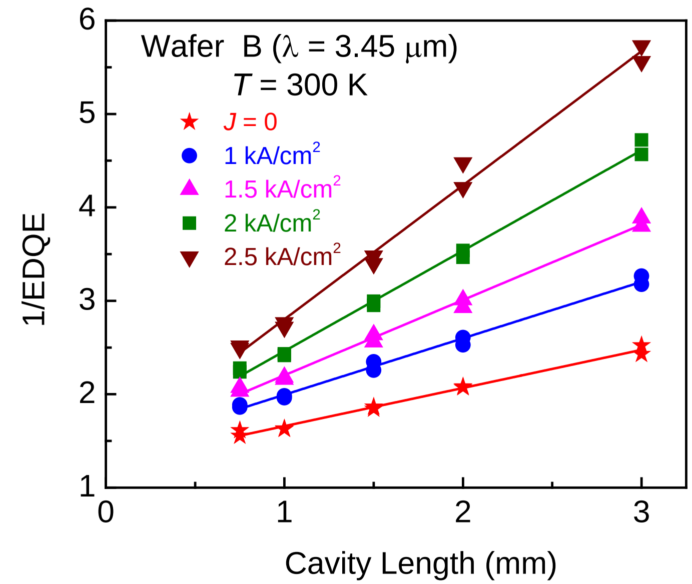
All ICLs from NRL (& elsewhere) show substantial droop above I_{th} – Why?

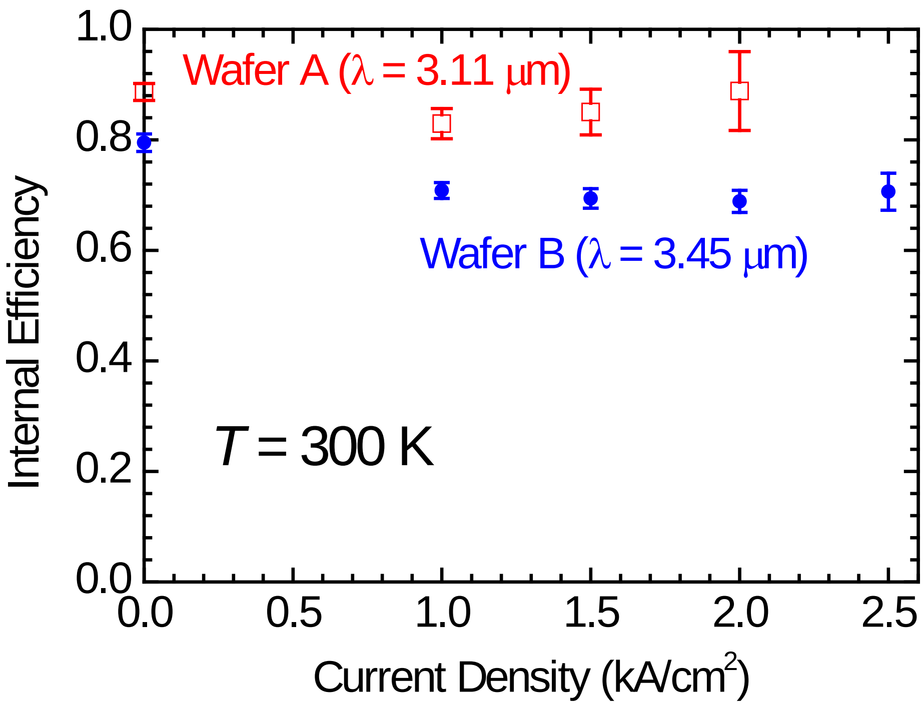
Pulsed data indicate substantial non-thermal component

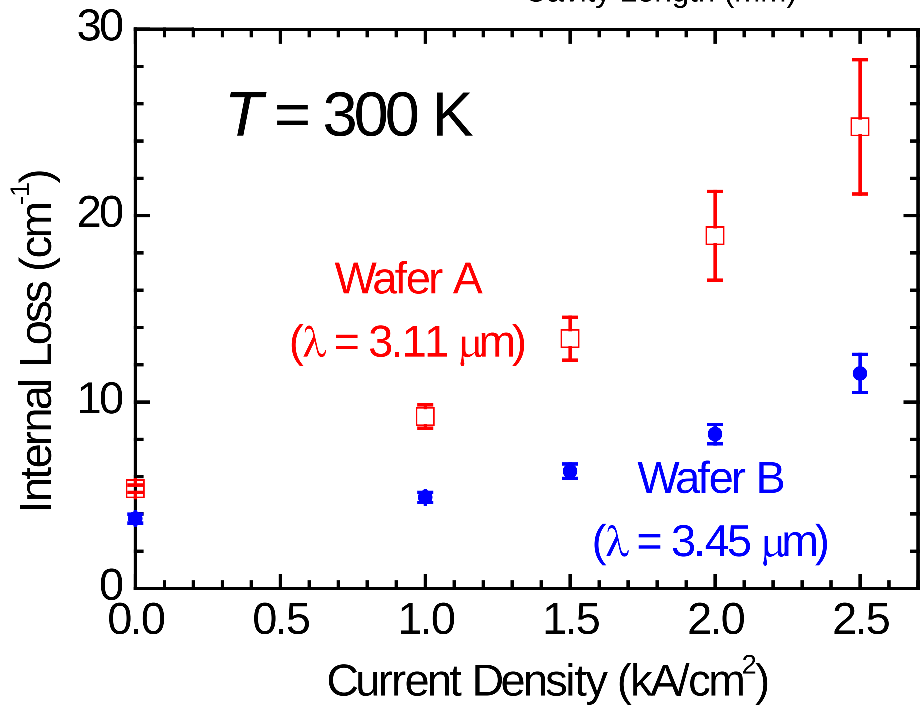
CAVITY LENGTH INVESTIGATION vs. J

- ***For 2 wafers:** Measured EDQEs for 5 cavity lengths, 5 current densities, 3 temperatures*
- ***Extracted internal efficiency from intercept & internal loss from slope***

[Merritt et al., submitted to Appl. Opt.]







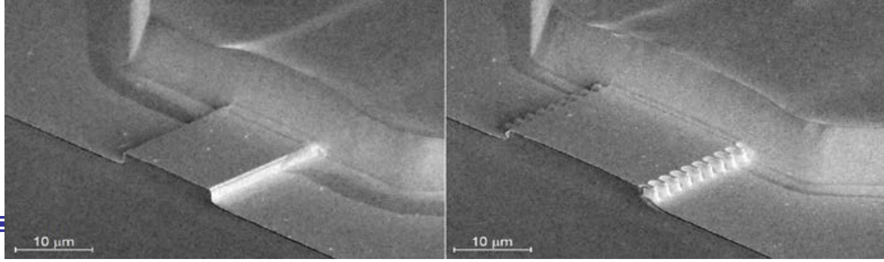
Droop at high currents clearly due to higher internal loss rather than lower internal efficiency – Effect much greater at shorter λ

CAVITY LENGTH SUMMARY

- **Efficiency droop with strong non-thermal component universal in ICLs**
  - **Attributable to increasing α_i with *J*, rather than decreasing η_i**
  - **Correlates with lack of carrier-density pinning in ICLs above threshold (from EL)**
  - **Type-I mid-IR diodes also fail to pin (although not as severe)**
- **η_i nearly independent of *J* (but why 70-90% rather than 100%?)**
- **With increasing *T* (up to 345 K), α_i relatively constant while η_i decreases**
- **Threshold gain *vs*. J_{th} from cavity length data follows expected logarithmic form, but magnitude > 20% below theory (?)**
- **Efficiency droop, & associated increase of α_i, greater at short λ**
  - **ICL performance in general degrades gradually at $\lambda \leq 3.1$ μm**
  - **Unexplained – Intuition says free carrier absorption & Auger decay should decrease rather than increase with decreasing λ**

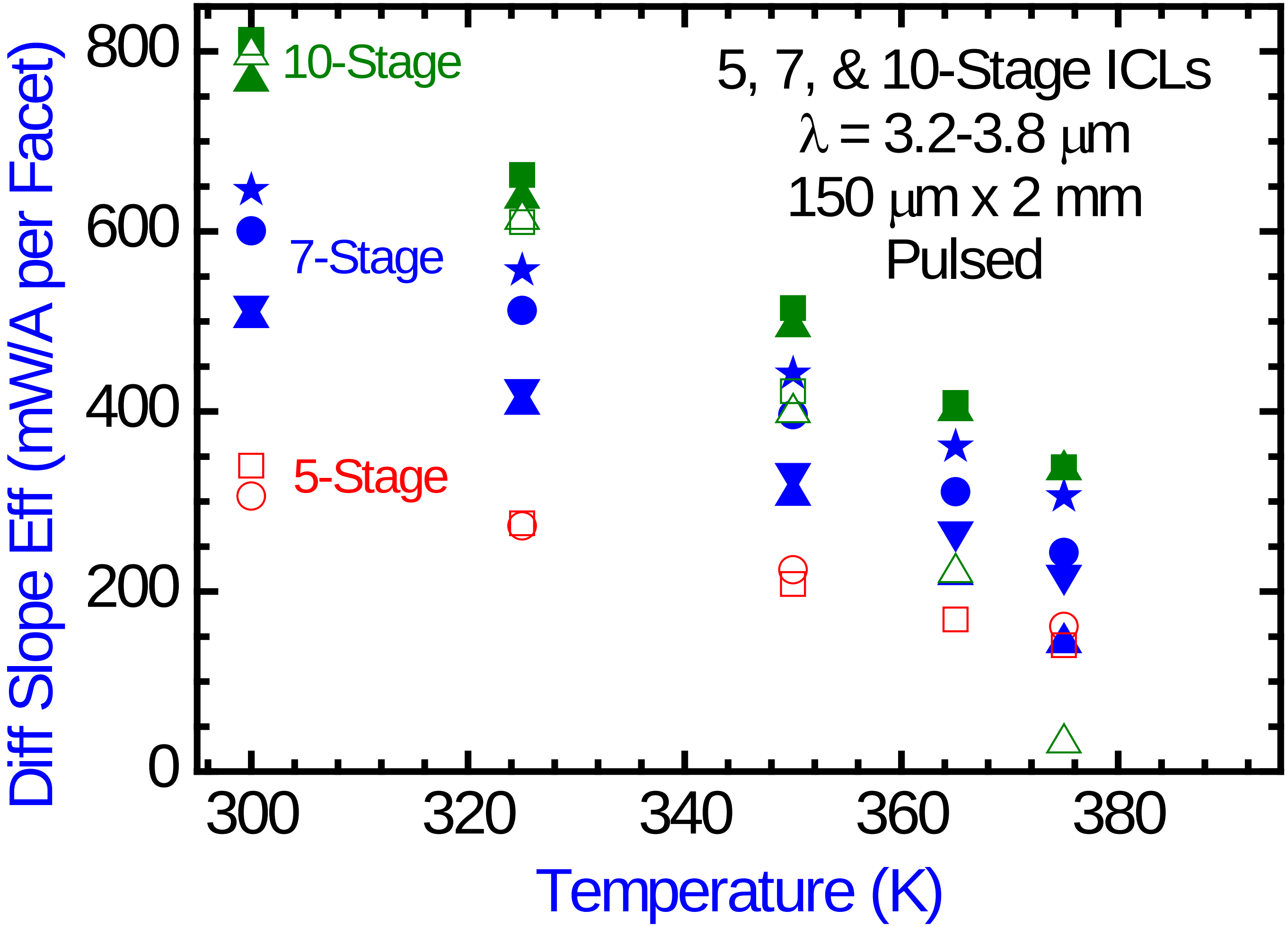
New information clarifies & quantifies unexplained observations, but does not resolve!

SUMMARY: CW POWER & BRIGHTNESS



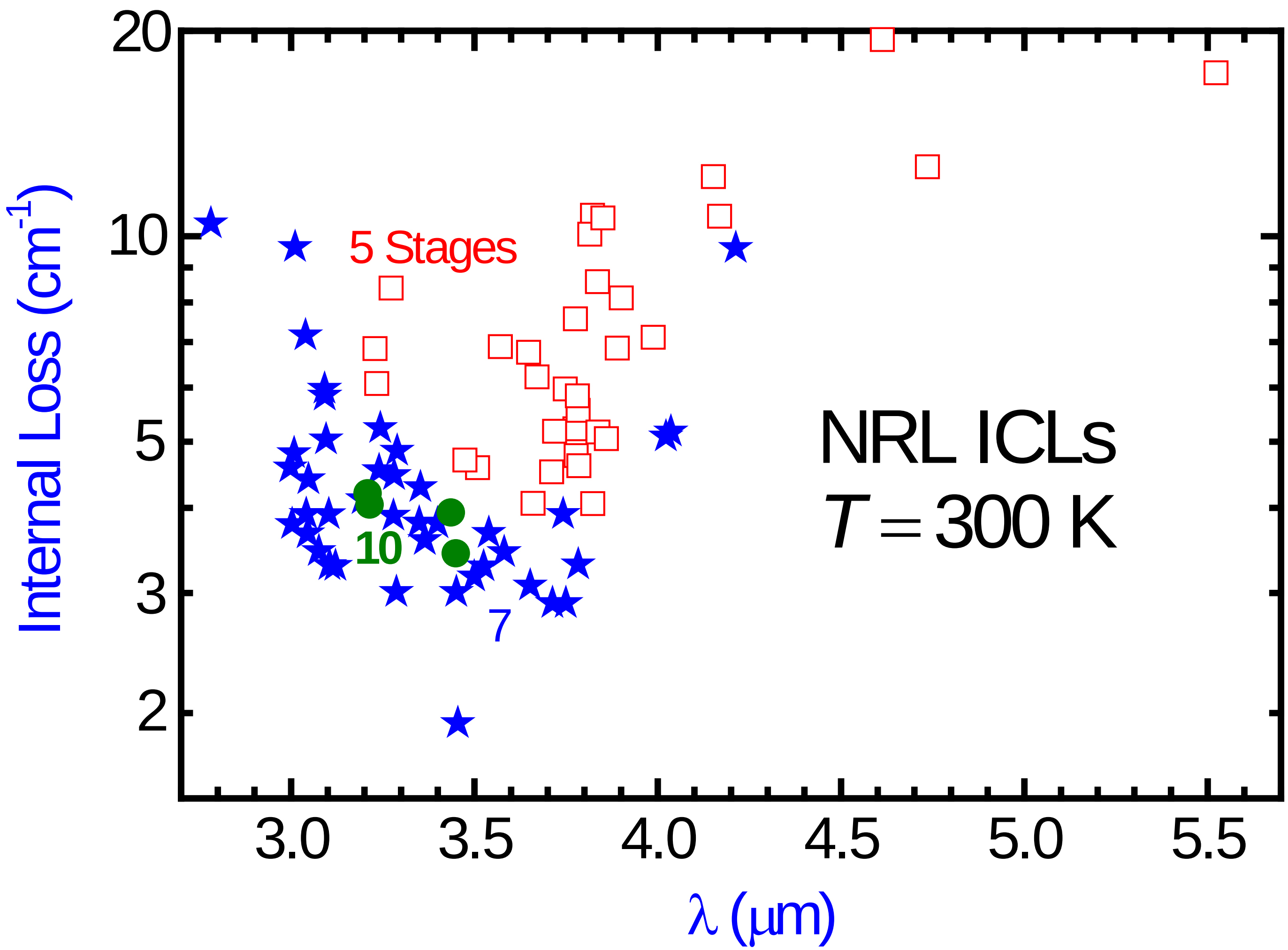
Year	Stages	λ (μm)	α_i (cm^{-1})	Ridge	Mount	L_{cav} (mm)	width (μm)	P_{max}^{25C} (mW)	WPE(P_{max}) (%)	M^2	Brightness *(P_{max}/M^2)*
2008	5	3.75	12.2	Straight	Epi-Up	3	9	10	0.7	≈ 2	5
2009	5	3.67	6.6	"	"	3	10	59	3.1	≈ 2	30
2011	5	3.57	6.9	"	"	3	11	158	9.9	3	53
2012	5	3.66	4.5	Straight	Epi-Down	4	11	198	7.1	1.8	110
				Corrug.	"	"	25	305	6.5	2.2	139
2013	5	3.72	5.2	Tapered	"	4	5 - 63	403	7.0	2.3	175
2014	7	3.45	3.0	Corrug.	"	3	22	383	12.4	2.4	160
				"		"	28	522	10.3	3.1	168
				"		"	32	592	10.1	3.7	160

NEXT TRY 10 STAGES



EDQE comparable for 10-stage vs. 7-stage (Both greater than 5-stage)

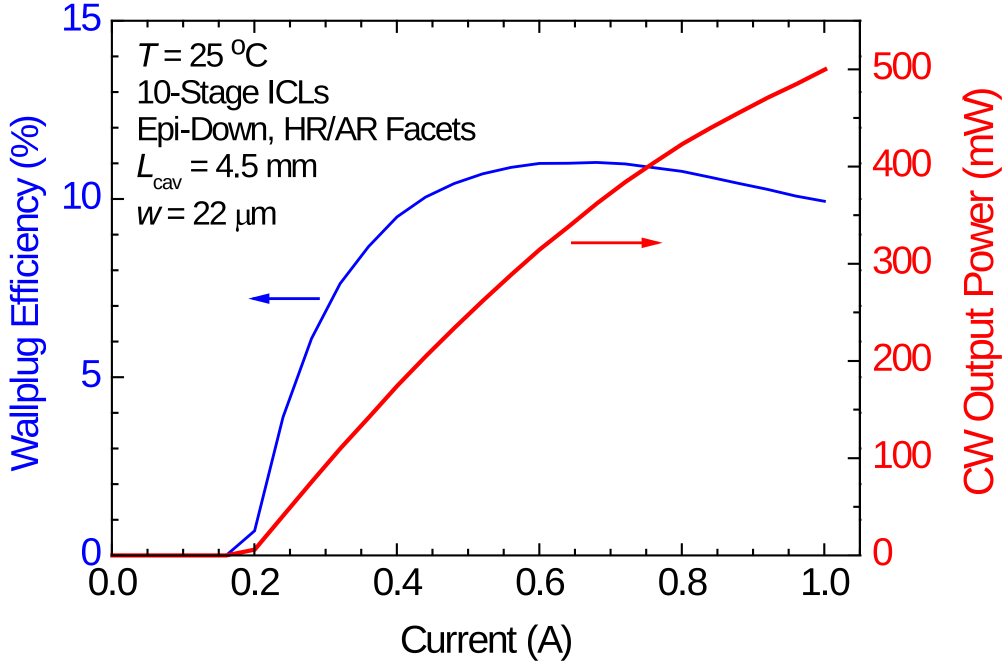
INTERNAL LOSS vs. WAVELENGTH

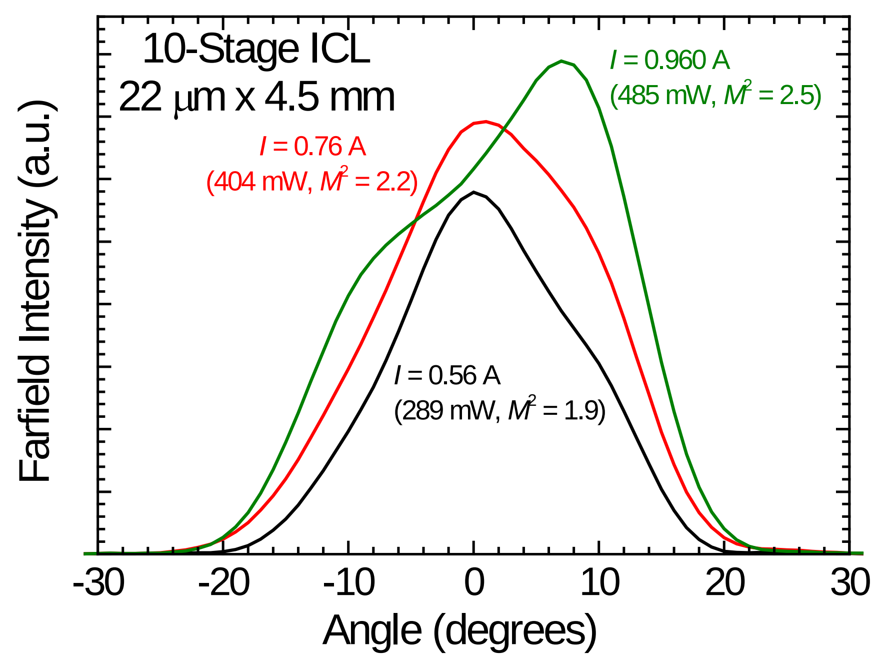


7-stage & 10-stage designs have comparable loss, on average

(But note increase when $\lambda < 3.2$ μm)

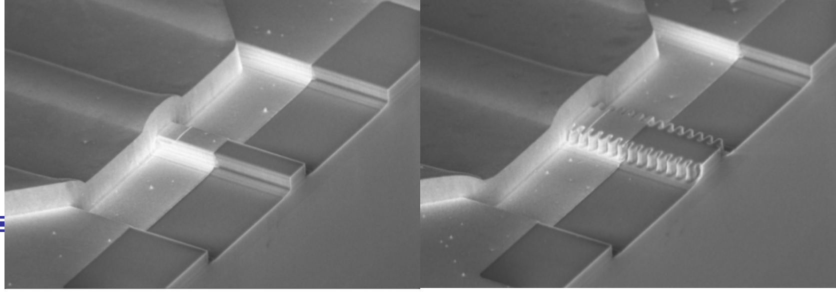
10-STAGE NARROW RIDGES: L-I & FAR-FIELD





Also: **P_{max}^{cw} = 464 mW (WPE = 11.2%, M^2 = 1.9) @ 25 °C**

CW POWER & BRIGHTNESS SUMMARY



Year	Stages	λ (μm)	α_i (cm^{-1})	Ridge	Mount	L_{cav} (mm)	width (μm)	P_{max}^{25C} (mW)	WPE(P_{max}) (%)	M^2	Brightness (P_{max}/M^2)
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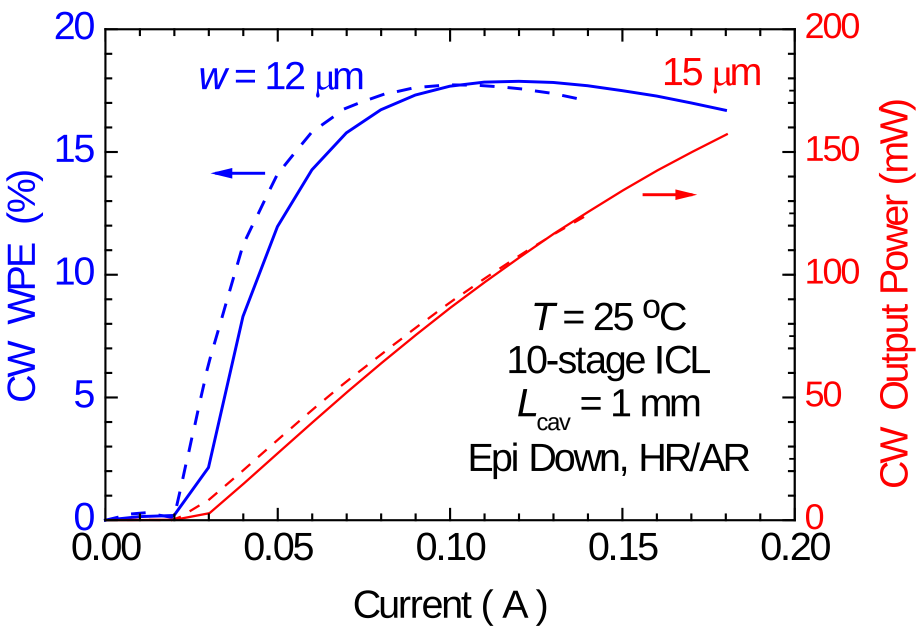
	10	3.45	3.4	Corrug.	"	4.5	18	464	11.2	1.9	245
	7	3.11	3.3	Corrug.	"	4.5	18	326	6.9	1.3	243

RECORD ICL WALLPLUG EFFICIENCIES

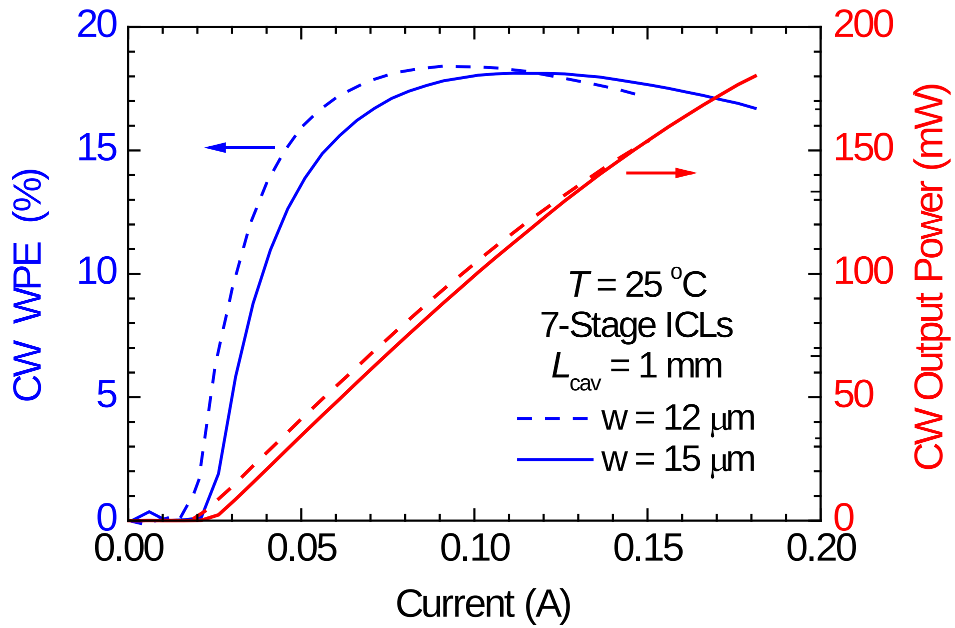
With shorter (1 mm) cavity & straight sidewalls:

$\lambda \approx 3.4\ \mu m$

10-Stage

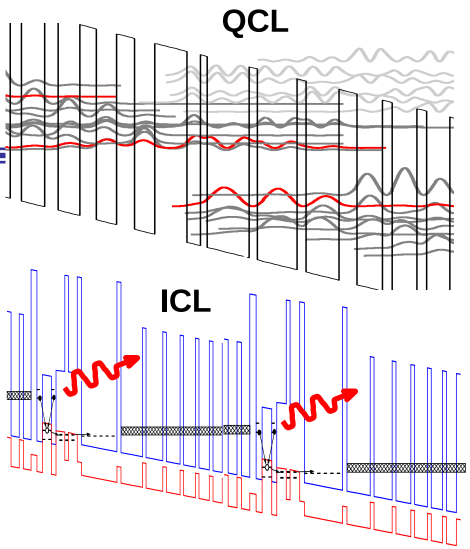


7-Stage



CW WPEs for 4 devices from 2 wafers (7-Stage & 10-Stage): 17.8-18.4%

QCL vs. ICL



- Older QCLs much more mature & widely studied
- λ = 3-4 μm: ICLs generally preferred
  - QCLs now produce P_{max}^{cw} > 1 W @ RT, but with higher threshold & lower efficiency
- λ = 4-6 μm: QCL sweet spot for high power (Up to 5 W cw demonstrated)
  - But ICL still preferred in applications requiring low power from ultra-compact battery-operated package (most laser spectroscopy)
- λ = 2.5-15 μm LEDs: Only ICLs suitable for top emission
- λ = 6-150 μm Lasers: QCLs the *only* option (ICL loss too high)
- *Conclusion:* QCLs & ICLs more complementary than competitive