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HIGH-EFFICIENCY INTERBAND CASCADE LASERS

2nd International Conference on Lasers, Optics, and Photonics
Philadelphia, PA, Sept. 8, 2014

Charles D. Merritt, William W. Bewley, Chul Soo Kim, Chadwick L. Canedy, Joshua Abell, Igor Vurgaftman, & Jerry R. Meyer

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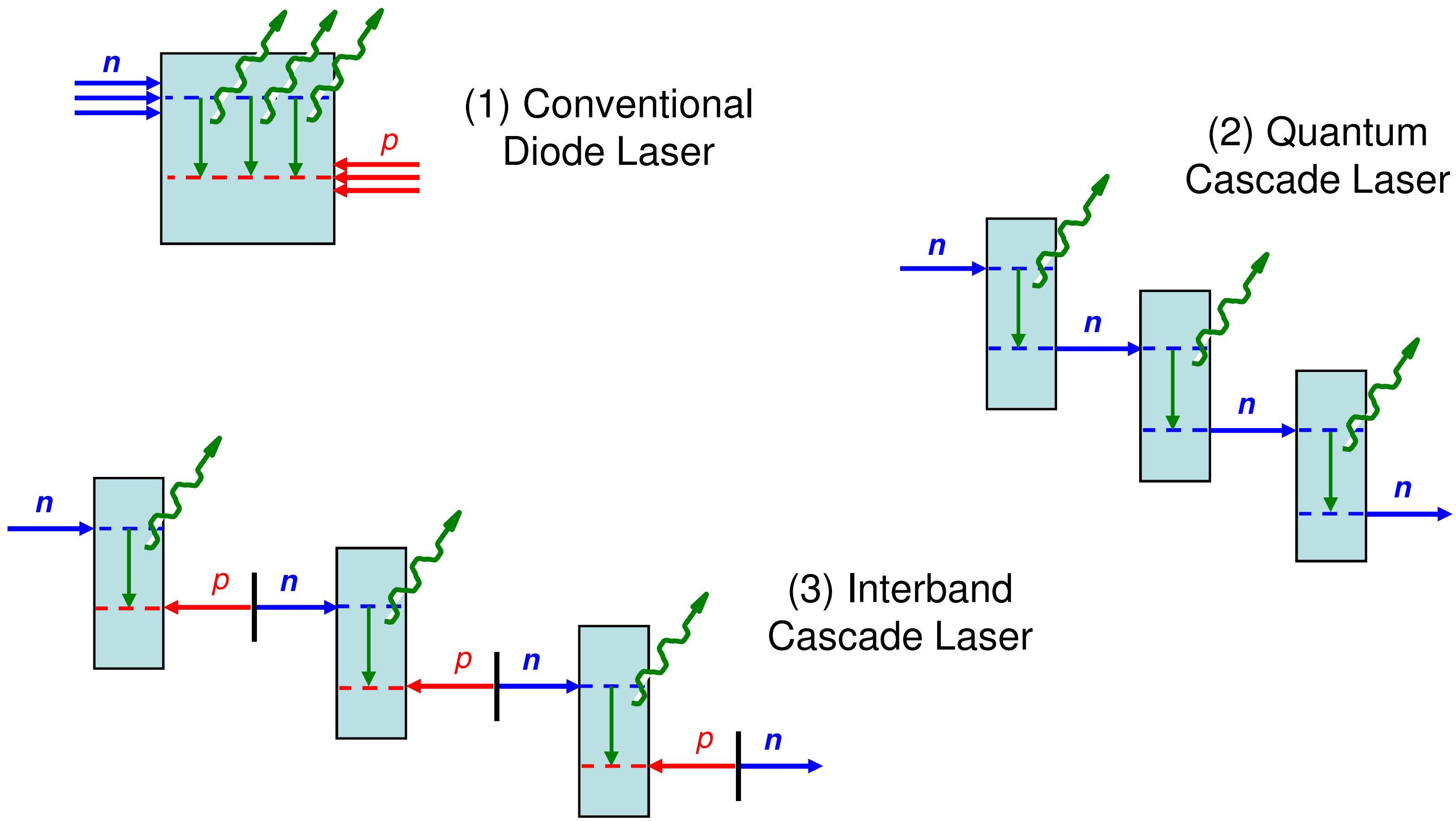
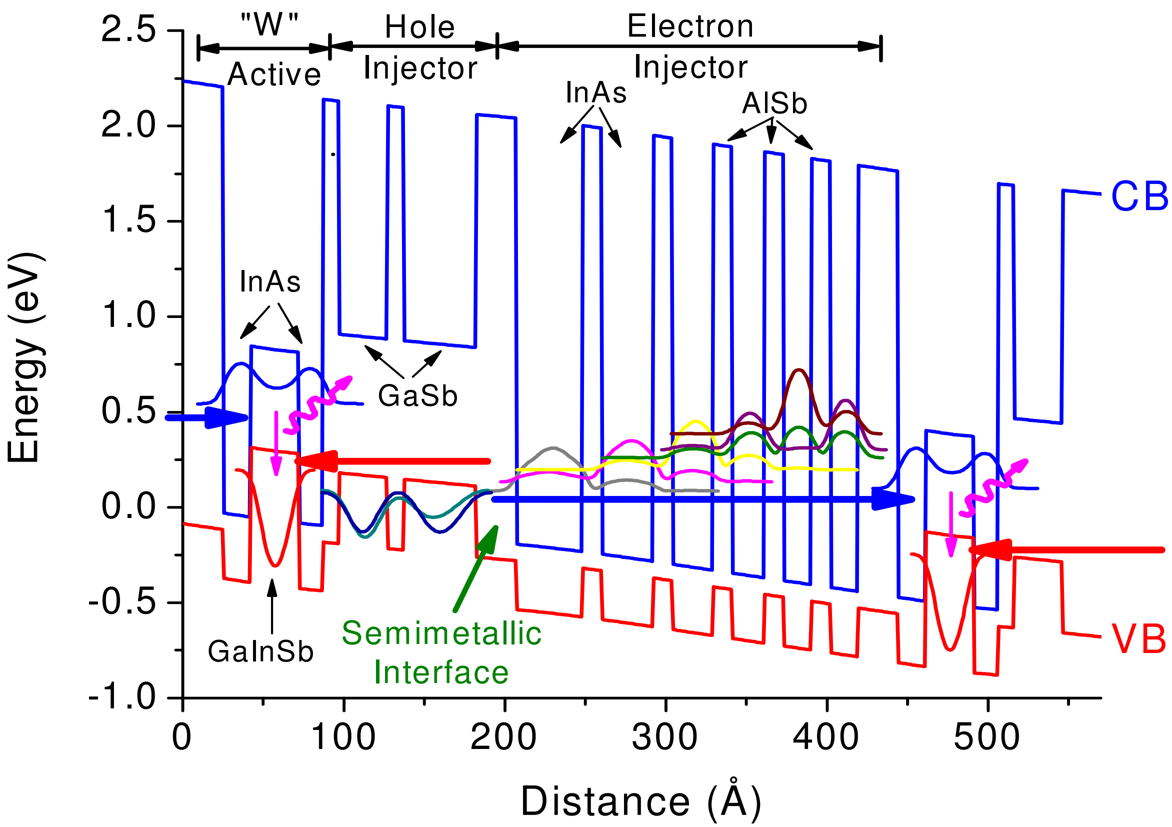
3 DISTINCT WAYS TO PROVIDE CARRIERS FOR POPULATION INVERSION



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

THE INTERBAND CASCADE LASER



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

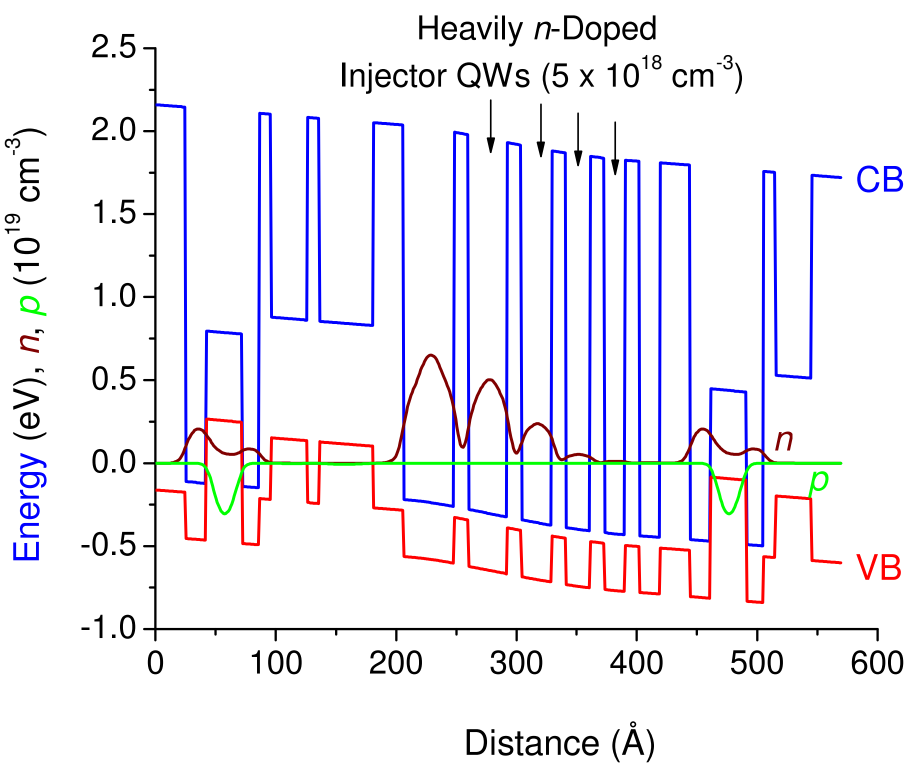
Design Improvements: **NRL (1996)**

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

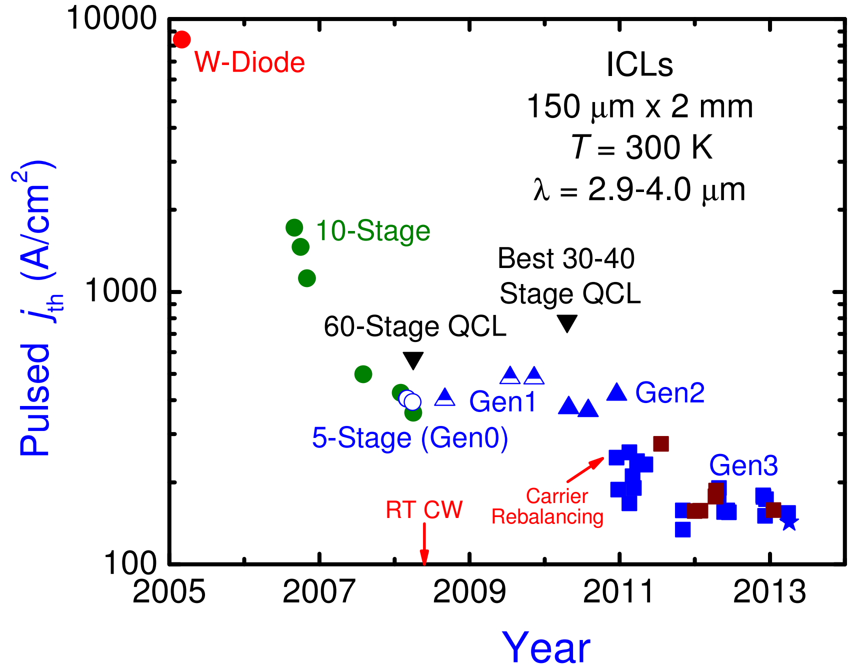
Further Development: **ARL, Maxion, JPL, U. Oklahoma, U. Würzburg, Nanoplus, U. St. Andrews**

RT cw operation: **NRL (2008)**

REBALANCING EFFECT ON THRESHOLD



[Vurgaftman et al., Nature Com. 2, 585 (2011); U.S. Patent Application 13/422,309 (2012); International Patent Application PCT/US12/29396 (2012)]

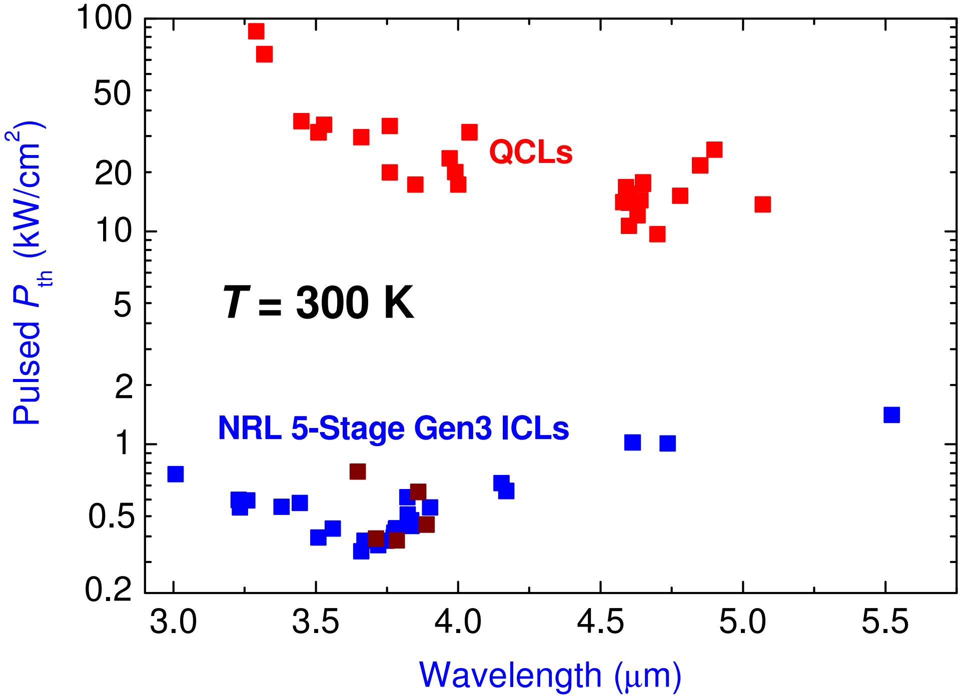


Major performance breakthrough with "carrier rebalancing", via heavy n-doping of electron injectors, to roughly equalize electron & hole populations in active region

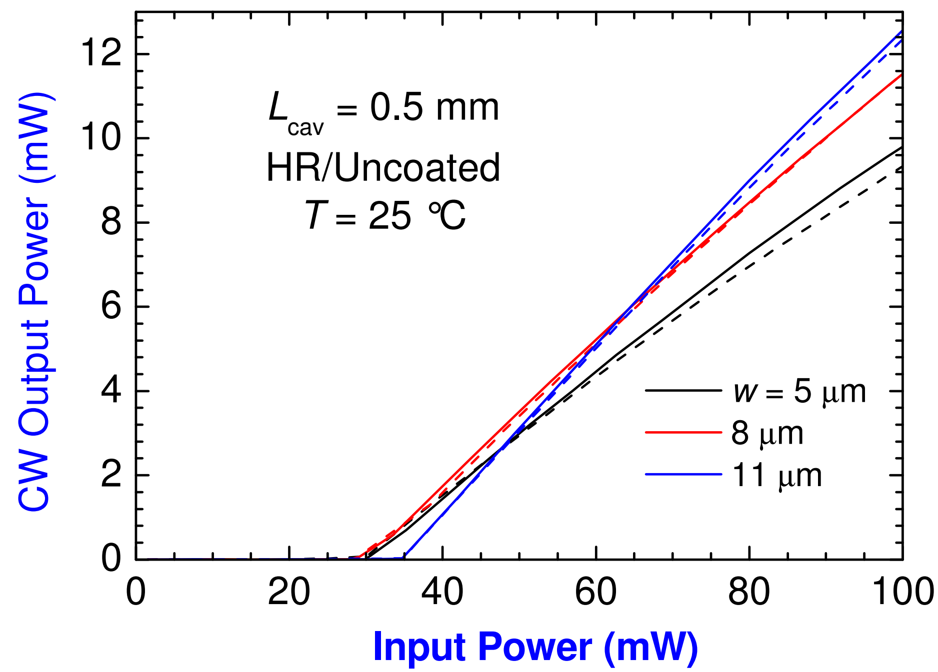
Dramatic threshold reduction compared to all previous ICLs

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

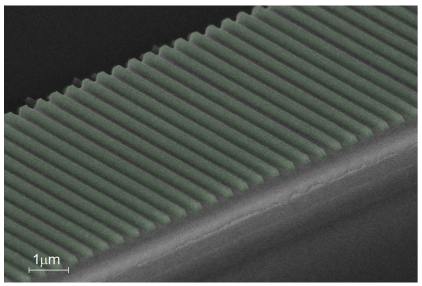
T = 25 °C: **Input for lasing < 30 mW**

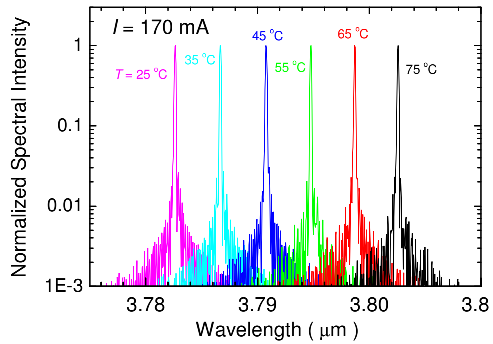
Best QCL result: **≥ 700 mW**

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

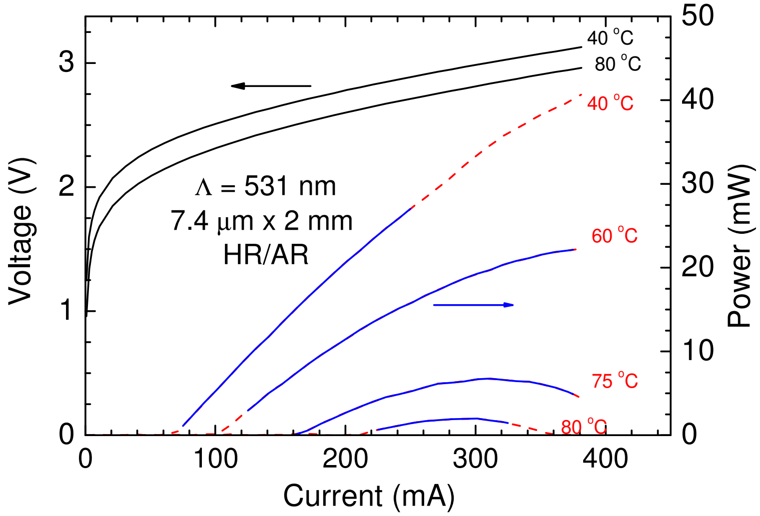
DFB ICLs

Grown, processed, & tested @ NRL: Grating etched into deposited Ge [Kim et al., APL 101, 061104 (2012)]





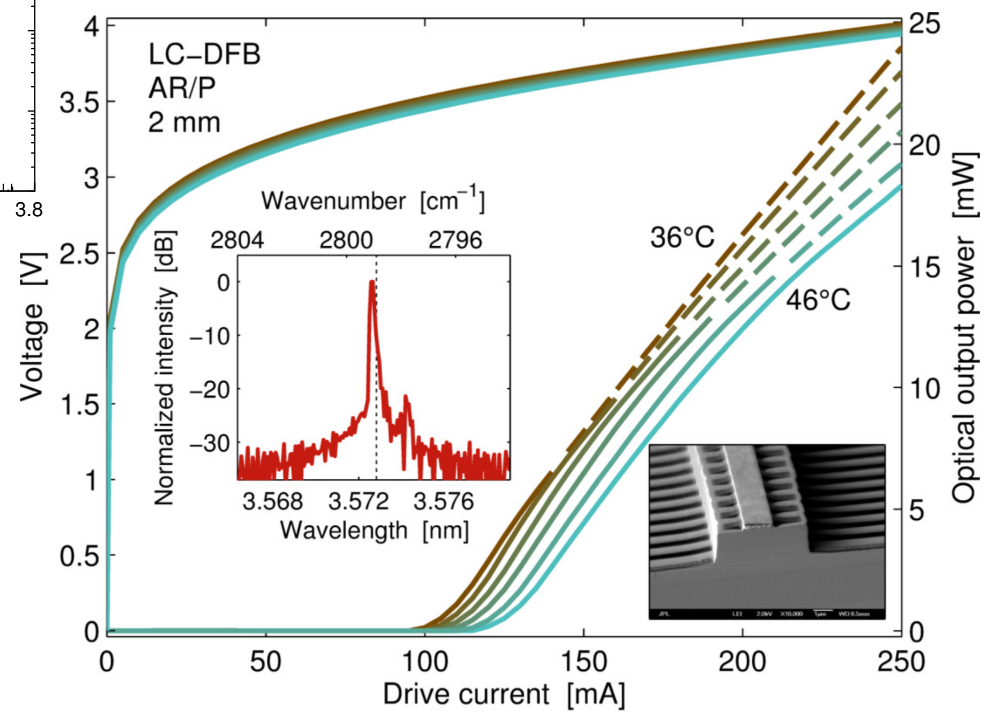
Single-mode tuning with temp: 21.5 nm
with current: 10 nm



P_{out}^{cw} = 27 mW @ T = 40 ºC, 1 mW @ 80 ºC
Threshold drive power = 280 mW @ 40 ºC

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

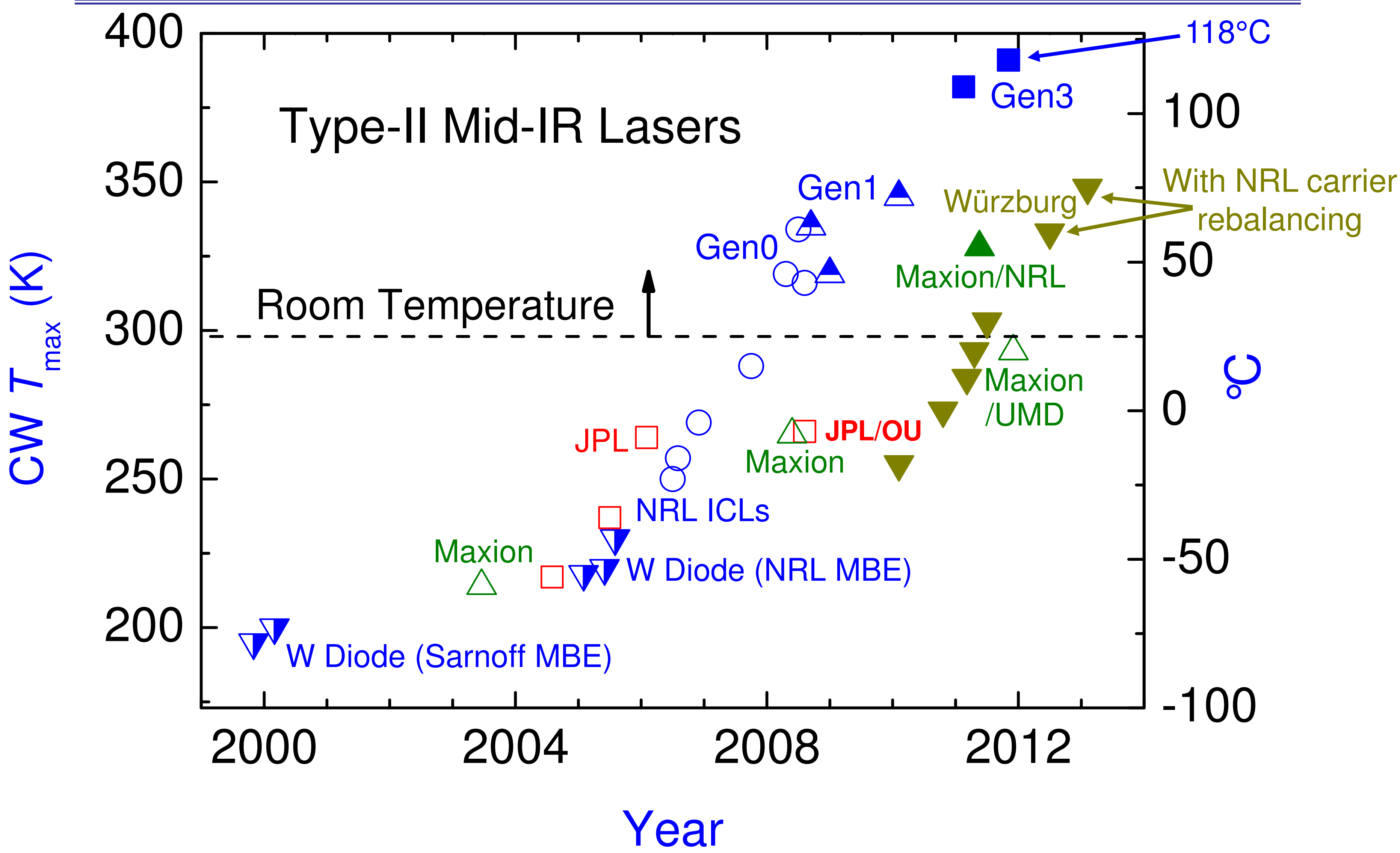
[Forouhar, et al., to be published]



P_{out}^{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

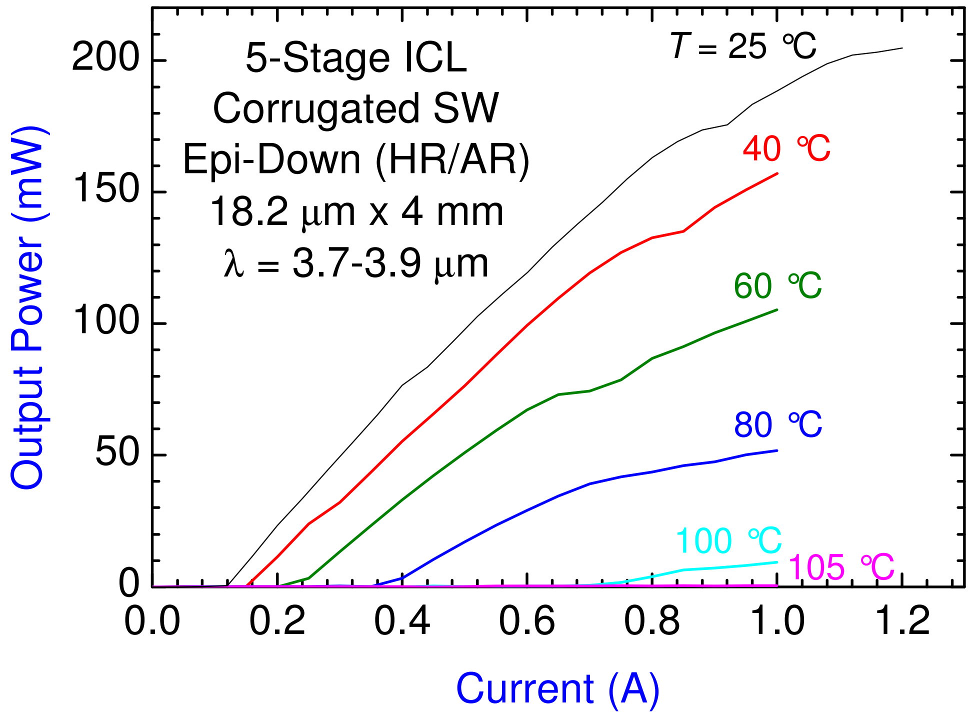
EPI-DOWN MOUNTING: HIGHER T_{max}^{cw}

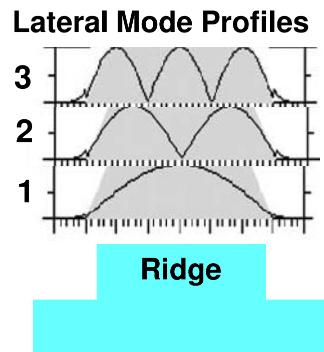
[Bewley et al., Opt. Expr. 20, 20894 (2012); U.S. Provisional Patent Application 61611800 (2012)]

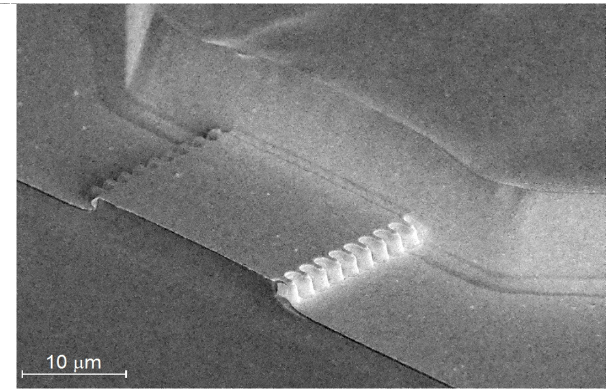


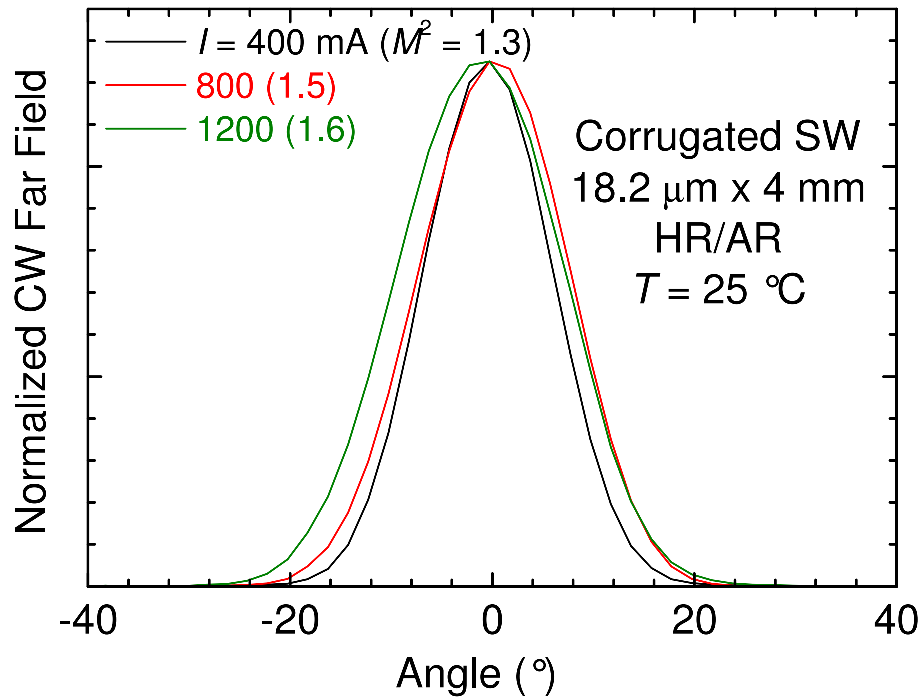
CORRUGATED-SIDEWALL ICLs

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





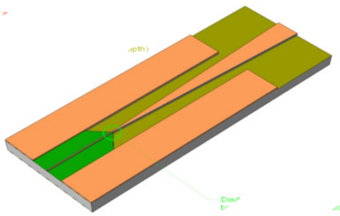




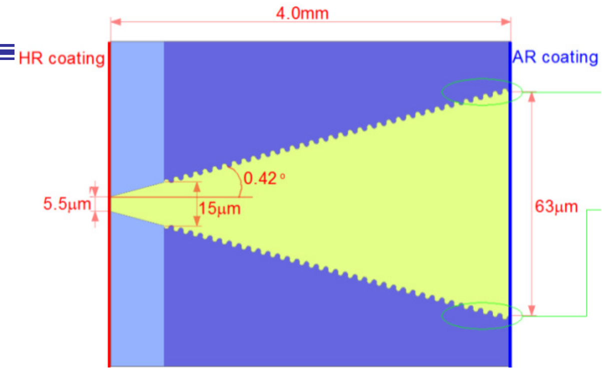
P_{max}^{cw} > 200 mW @ T = 25 ºC (M^2 = 1.6)

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

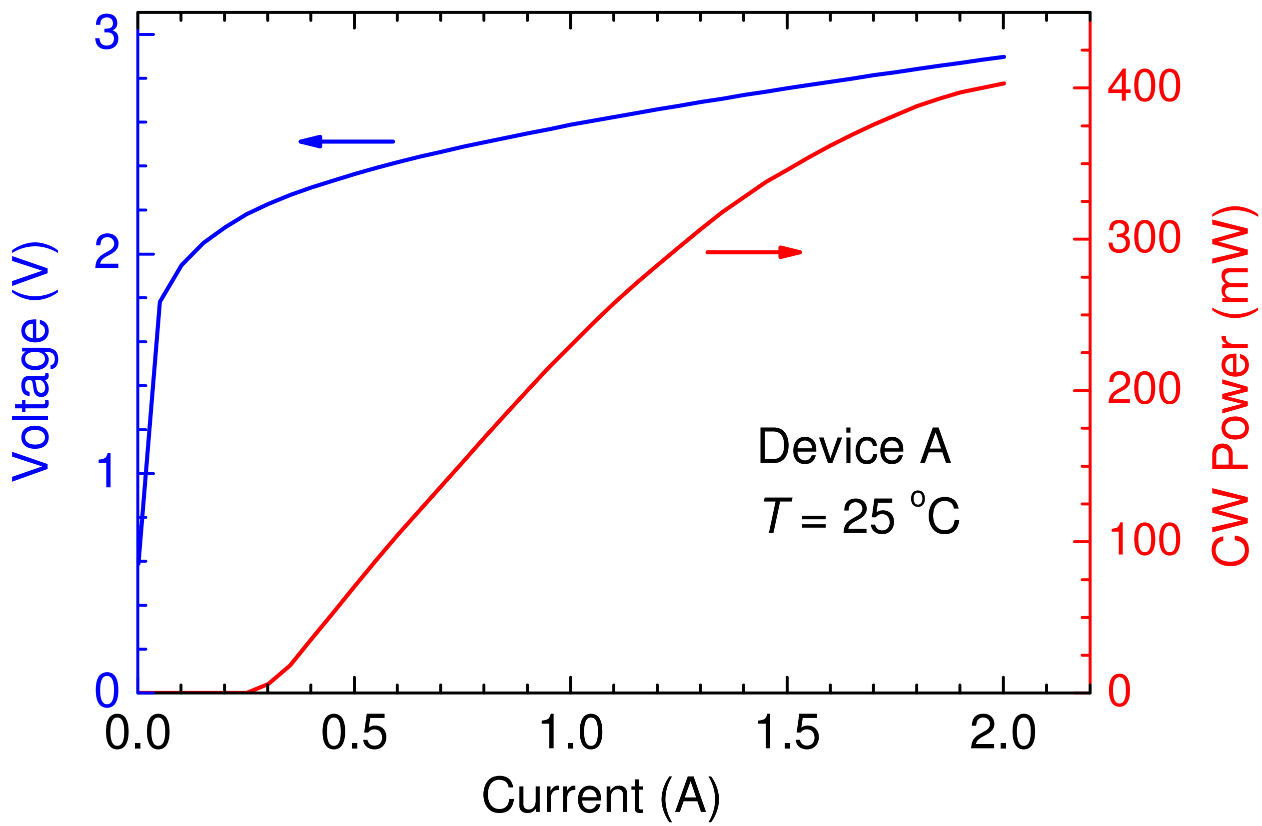
TAPERED ICLs

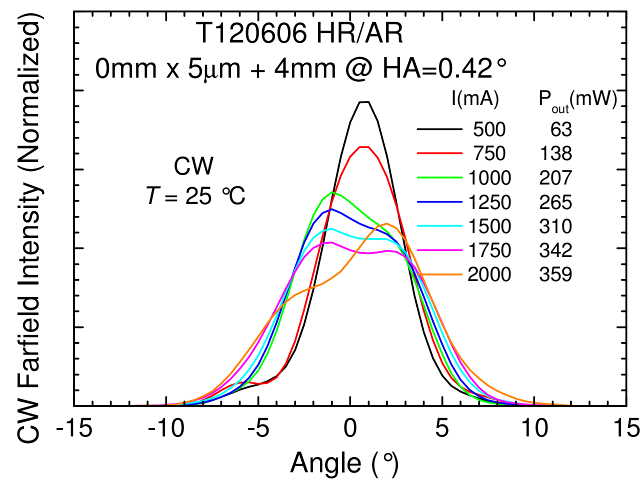


[Bewley et al., APL 103, 111111 (2013)]



Tapered ridge with no straight section

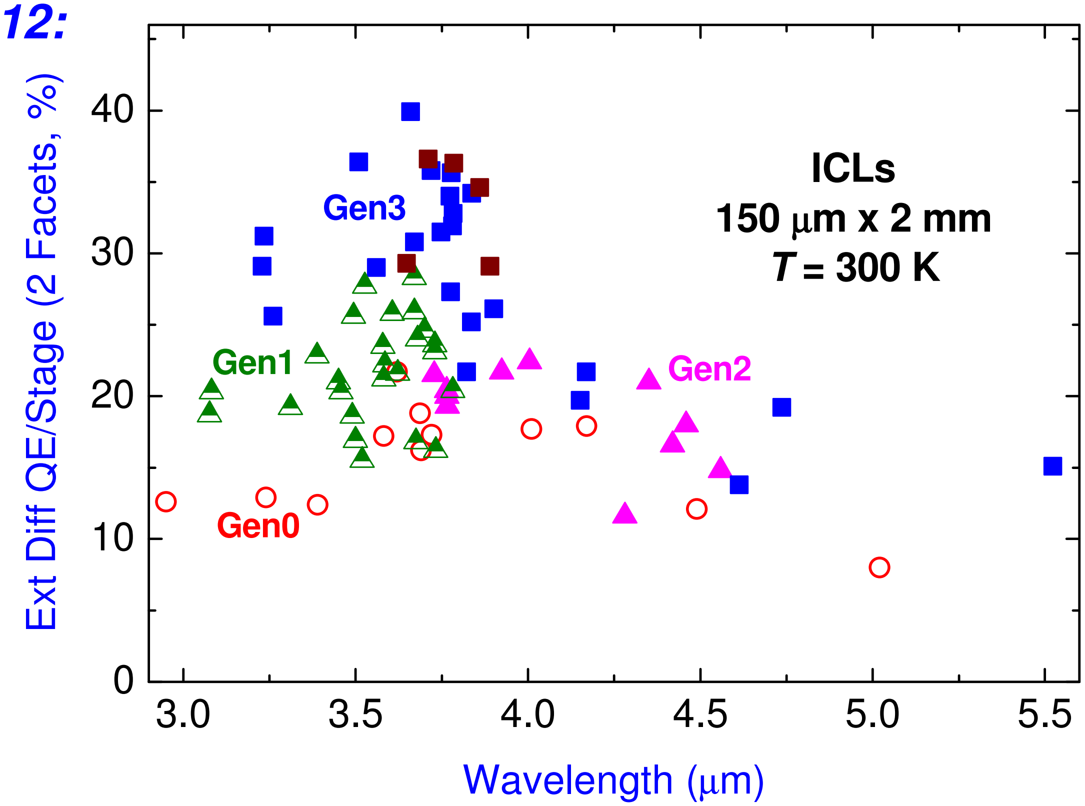




P_{max}^{cw} **(25 ºC) = 403 mW (**M^2 **= 2.3), WPE = 7.0% @** P_{max}

TO FURTHER ENHANCE POWER & BRIGHTNESS: INCREASE EFFICIENCY

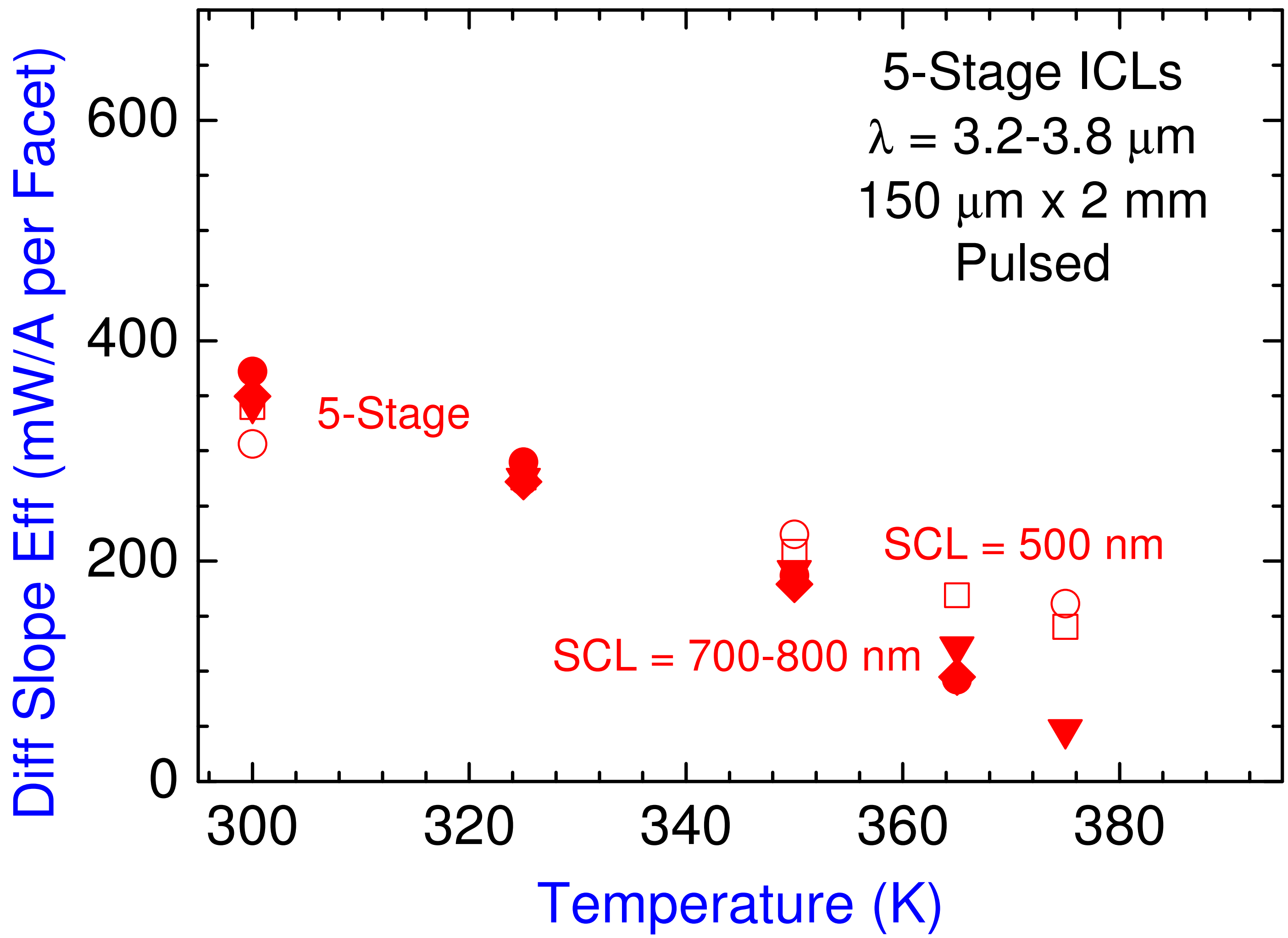
As of October 2012:



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

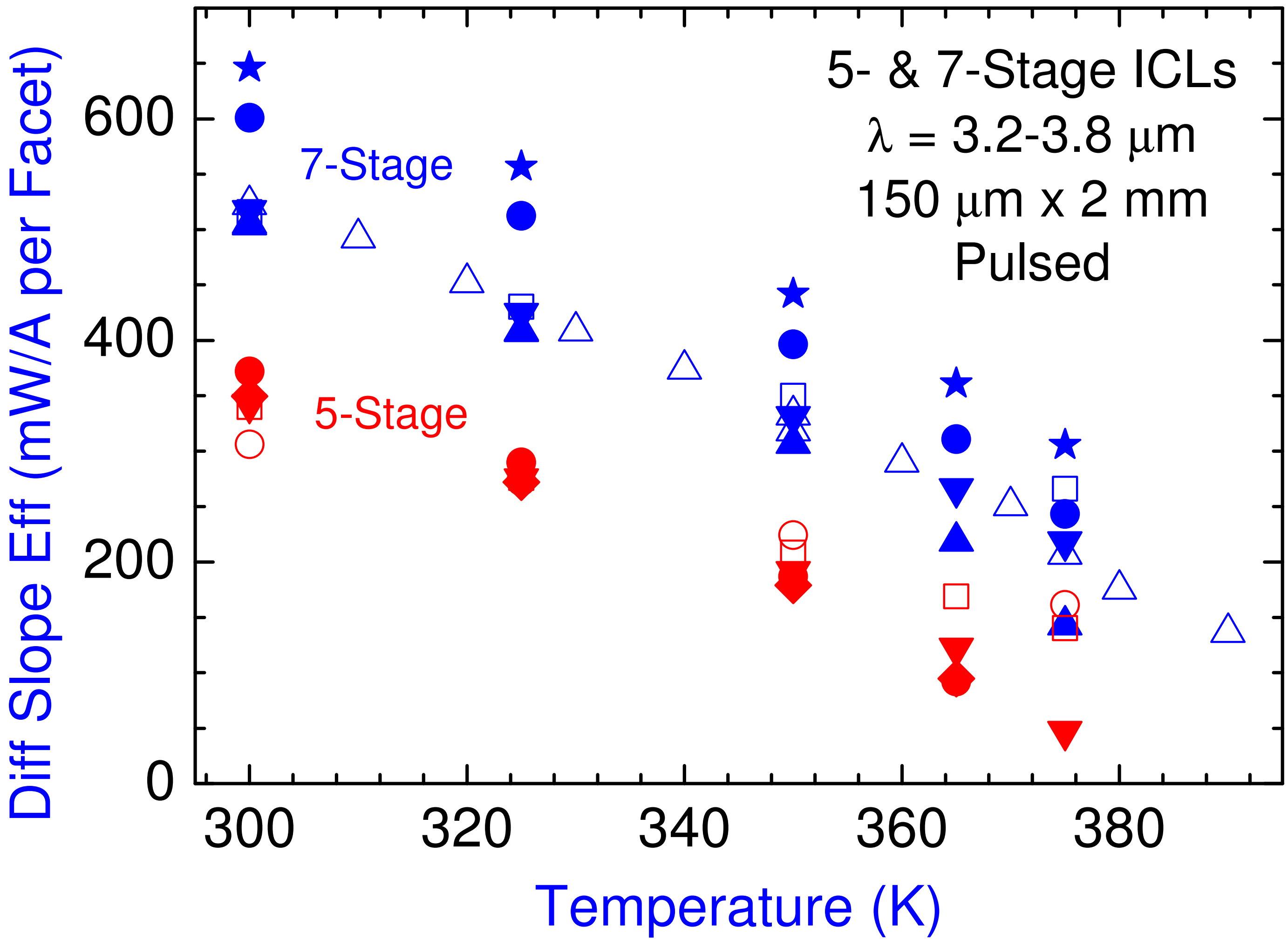
FIRST 5 STAGES WITH THICKER SCLs



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)]

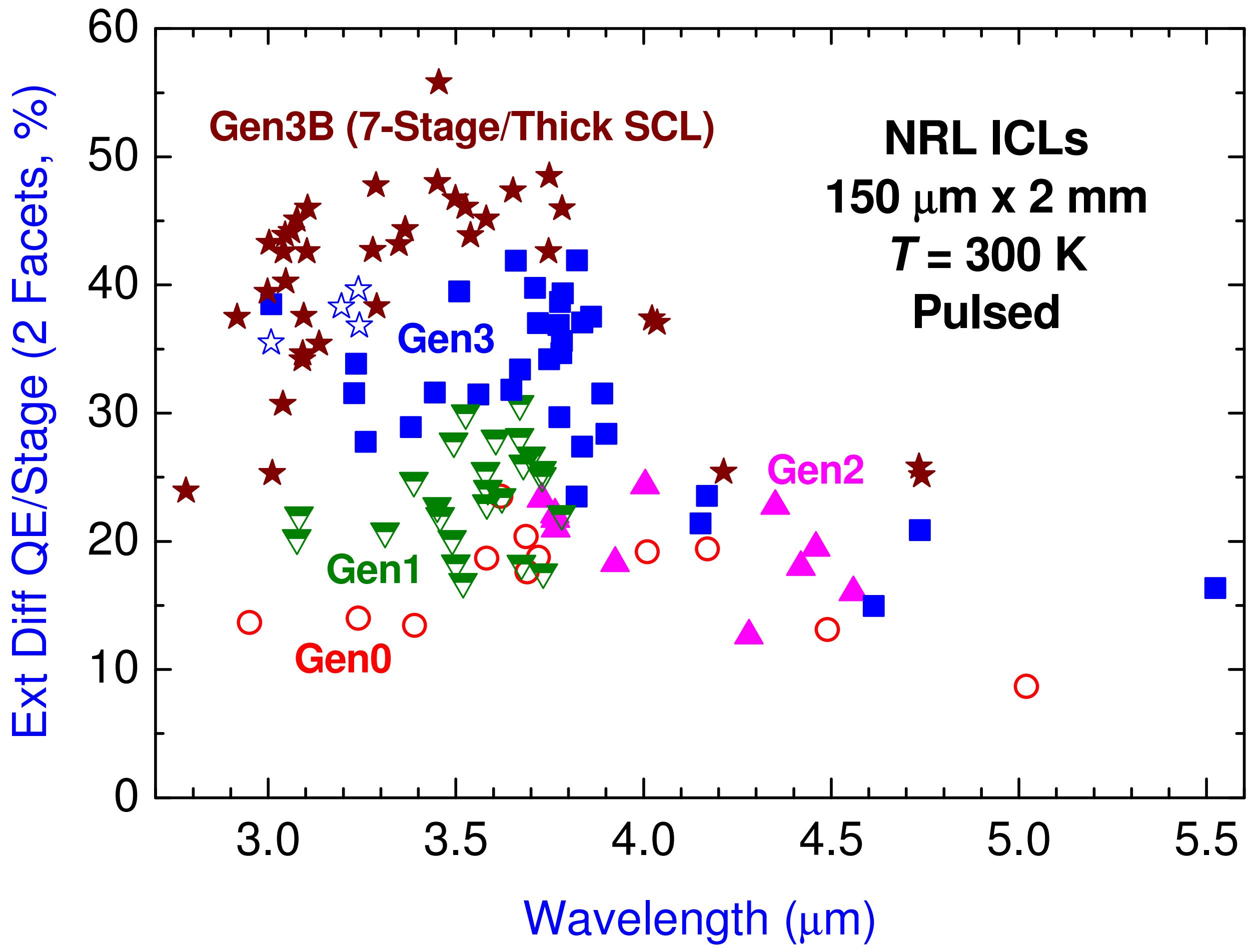


Thick SCLs increase advantage at 300 K, while retaining sufficient gain at high T

Even better news: $Slope_7/Slope_5$ > 7/5 indicates lower loss!

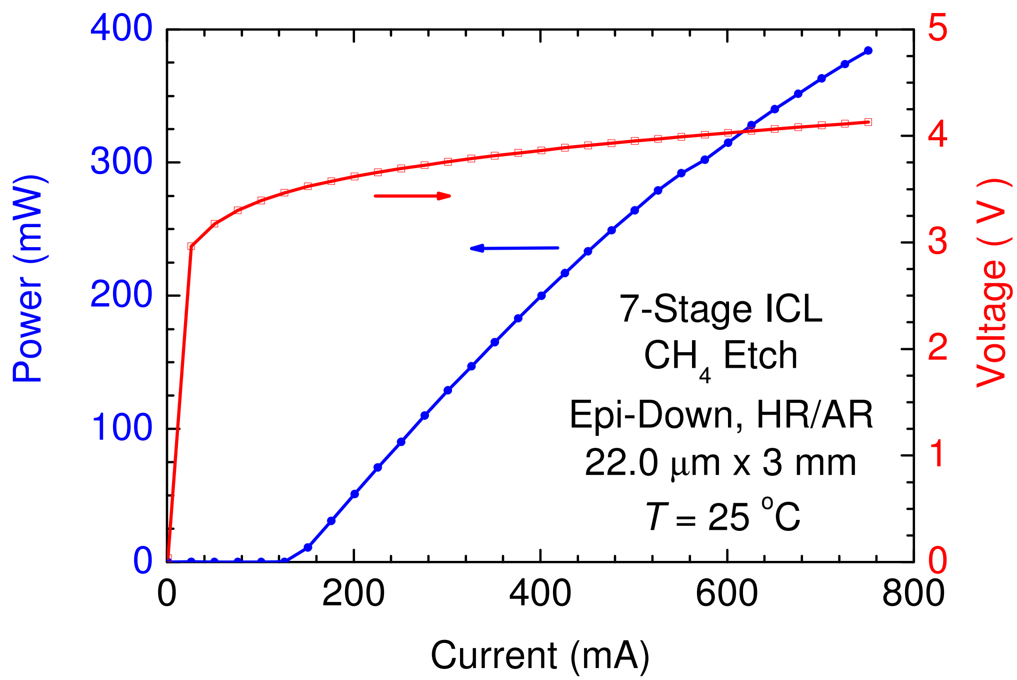
EXTERNAL DIFFERENTIAL QUANTUM EFFICIENCY

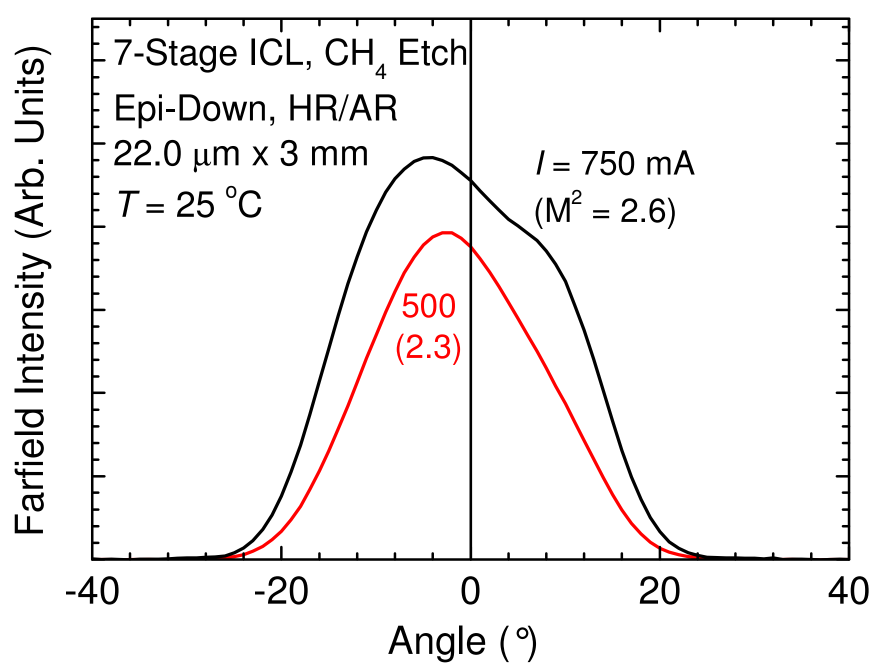
Result is significantly higher EDQE:



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

CW POWER & FAR FIELD PROFILE

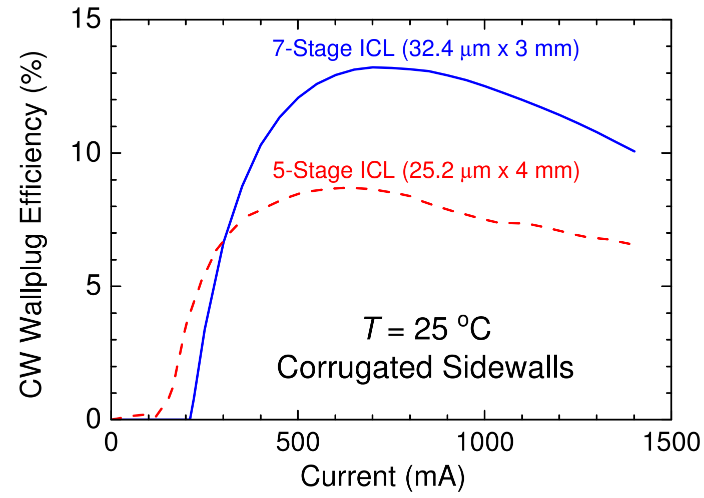




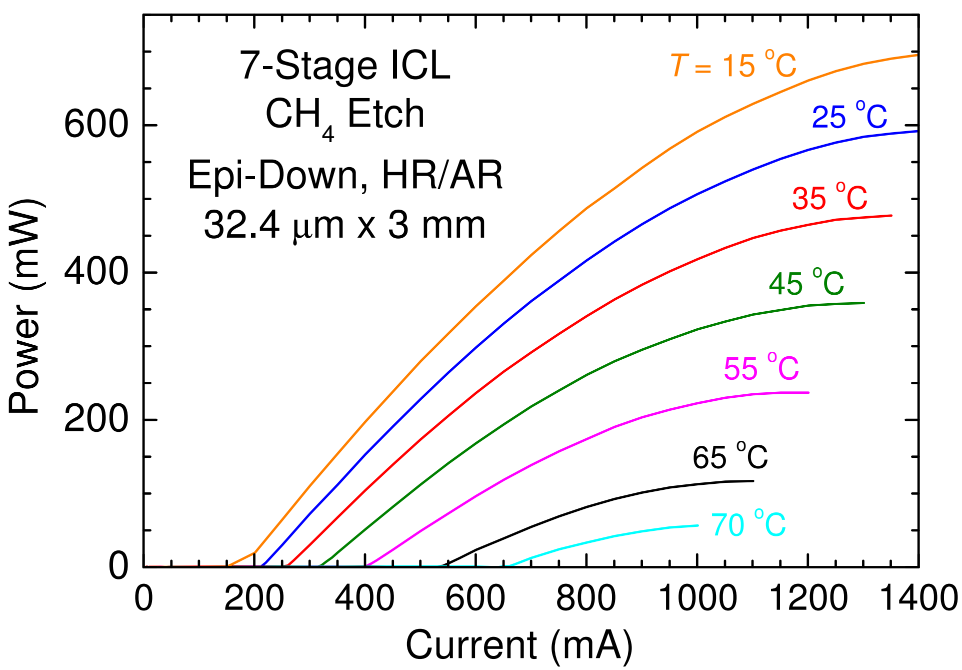
P_{max}^{cw} = 384 mW in high-quality beam (M^2 = 2.6)

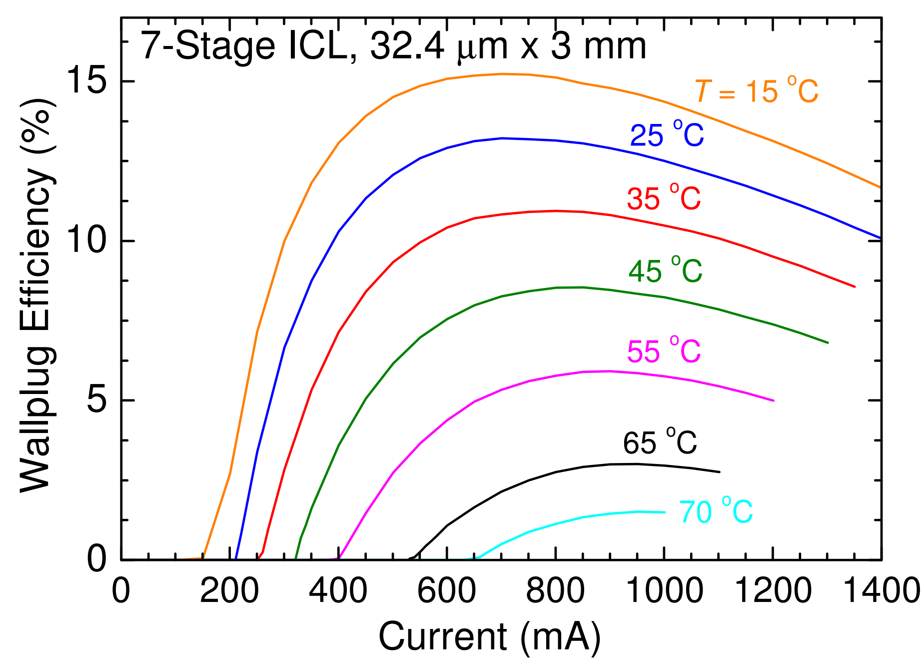
WPE = 12.4%

WIDER RIDGE (w = 32 μm)



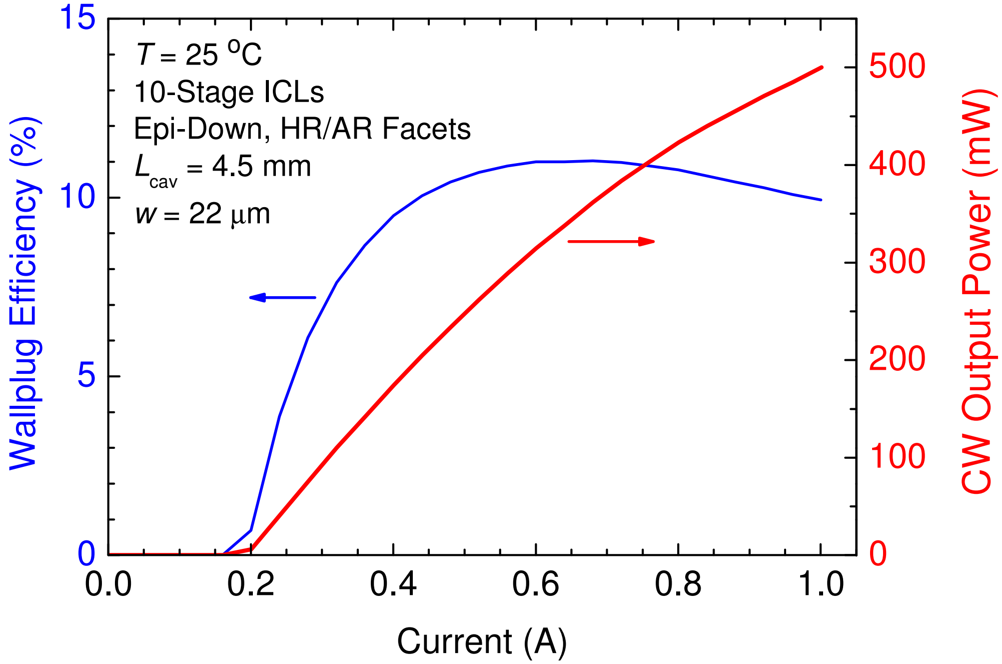
[Bewley et al., Opt. Expr. 22, 7702 (2014)]

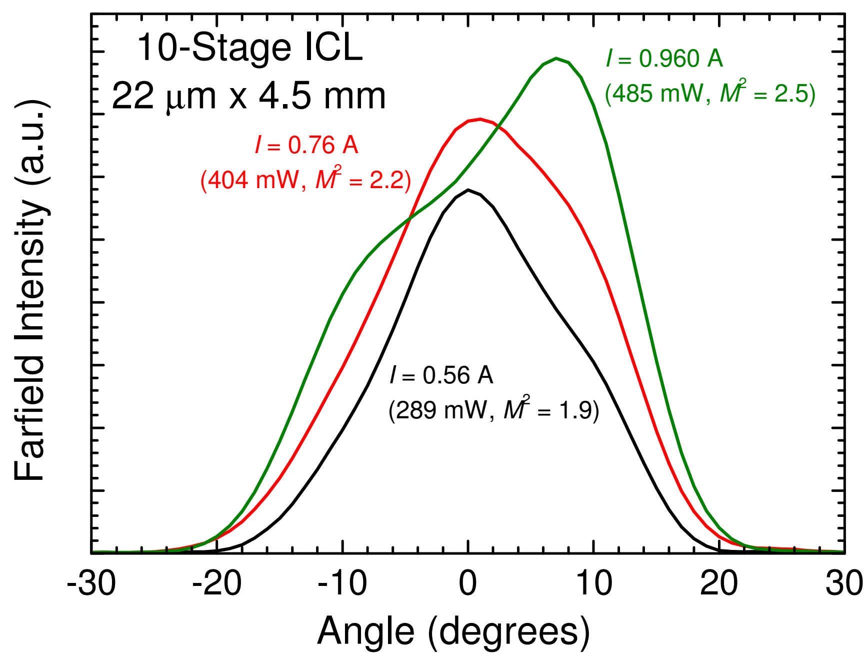




P_{max}^{cw} up to 592 mW (WPE = 10.1%, M^2 = 3.7) @ 25 °C; 696 mW (11.7%) @ 15 °C

LATEST RESULTS: 10 STAGES (λ = 3.45 μm)

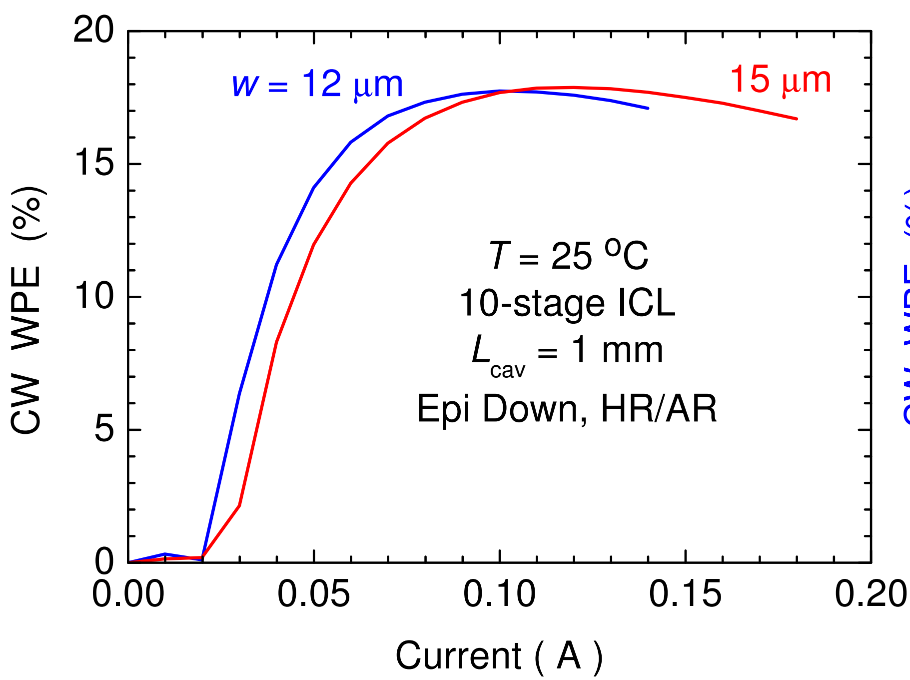


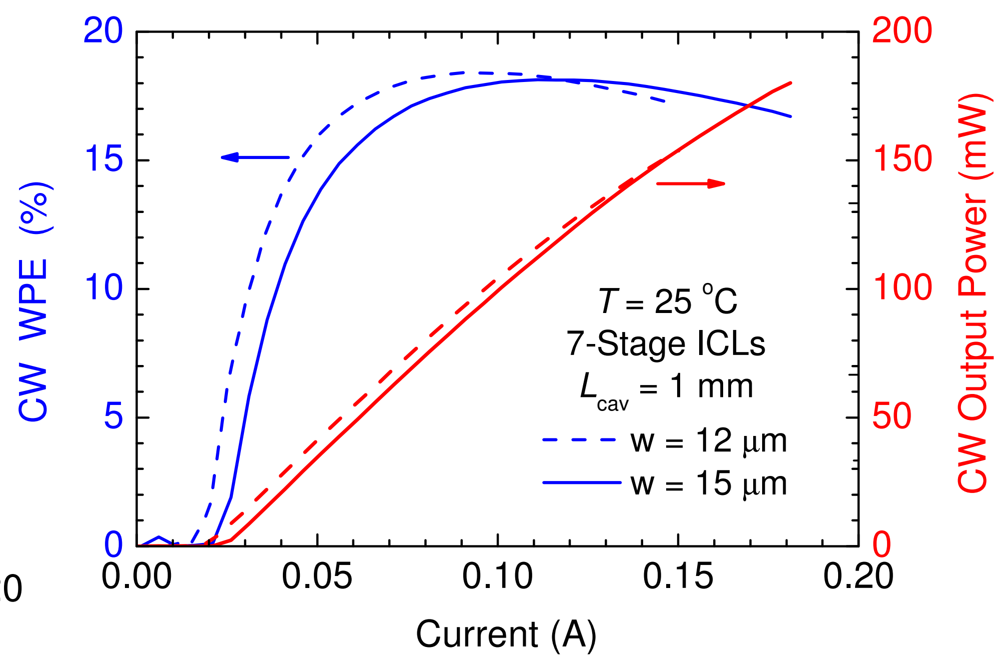


Also: P_{max}^{cw} **= 464 mW (WPE = 11%, M^2 = 1.9) @ 25 °C**

RECORD ICL WALLPLUG EFFICIENCIES

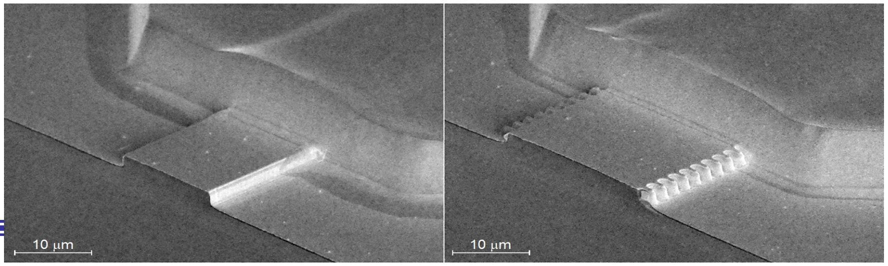
With much shorter 1 mm cavity:





CW WPEs for 4 devices from 2 wafers (7-Stage & 10-Stage): ≈18%

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	28	522	10.3	3.1	168
	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

QCL vs. ICL

- QCLs much more widely studied & matured, provide very high cw output powers
- ICLs provide much lower power dissipation, possibility for vertical emission, & minimal beam steering – also less mature, so more room for improvement
- λ = 3-4 μm: ICLs generally preferred
  - QCLs now produce P_{max}^{cw} > 1 W @ RT, but higher threshold, lower efficiency, & questionable yield thus far
- 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 (*e.g.* laser spectroscopy)
- λ = 2.5-15 μm LEDs: Only ICLs suitable for top emission
- λ = 6-150 μm Lasers: QCLs preferred (so far, high loss in ICLs)
- *QCLs & ICLs can complement each other throughout mid-IR*

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