MBE Growth of Terahertz Quantum Cascade Lasers

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Presentation Outline

- Introduction
- Issues associated with growth
- Robustness of Active Region designs
- Minor tweaks to Active Region
- Transfer of structures between growth reactors
- Summary

The Unipolar Semiconductor Laser

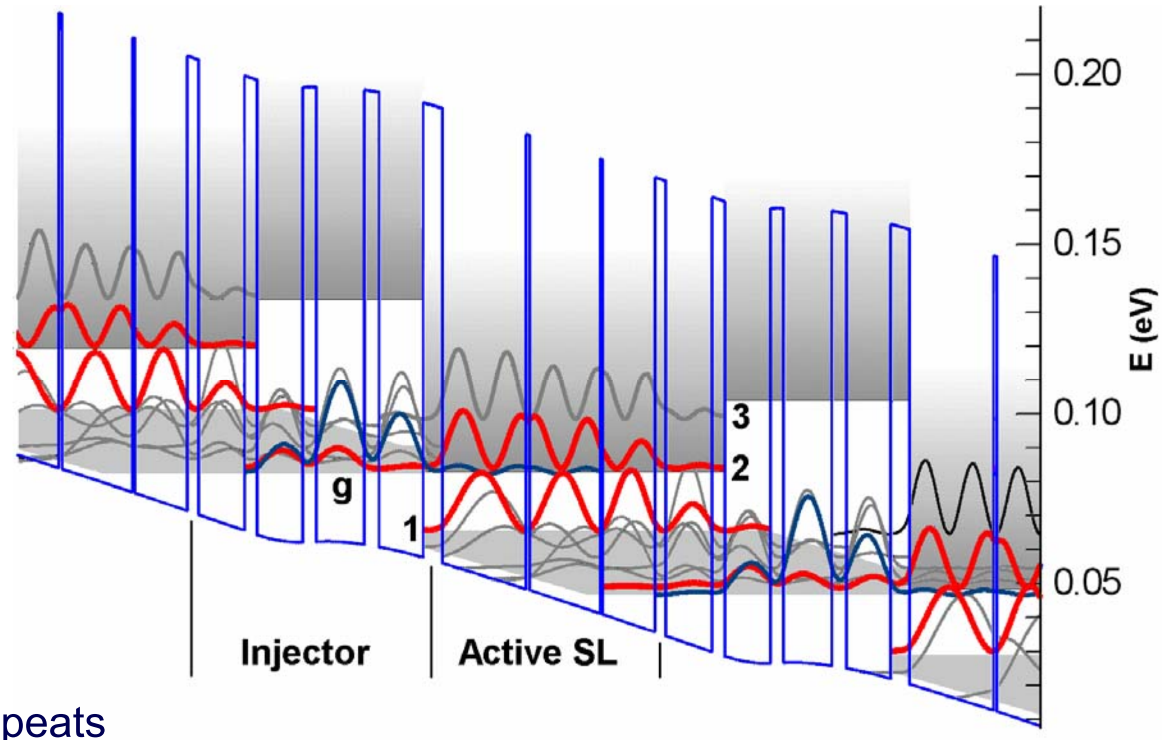
"materials by design":
band structure engineering through molecular beam epitaxy

- **1971**: amplification from intersubband transitions is first postulated by R. F. Kazarinov and R. A. Suris, **Sov. Phys. Semicond. p5,** *(Ioffe)*
- **1994**: QCL is first experimentally demonstrated in MIR by J. Faist et al. **Science 254, p553** *(Bell Labs)*
- **2002**: QC-lasers outperform other mid-IR lasers in many aspects R. Köhler et al. **Nature 417, p156** *(SNS Pisa/Univ Cambridge)*

What Grower Sees

Köhler *et al.*, Nature **417**, p156 (2002)

4.4THz chirped superlattice QCL AR



x104 Repeats

$Al_{0.15}Ga_{0.85}As/GaAs$

What Grower Sees

Final QCL device:

90-250 periods active region
12-18μm thick
1200 - 1500 layers
Some barriers ~6Å (~2MLs)
12-18hrs growth duration

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PUSHING BOUNDARIES OF GROWTH TECHNIQUES

- growth rate calibration
- growth rate stabilty
- inteface roughness

accuracy of layer thickness

Molecular Beam Epitaxy

Precise semiconductor growth technique

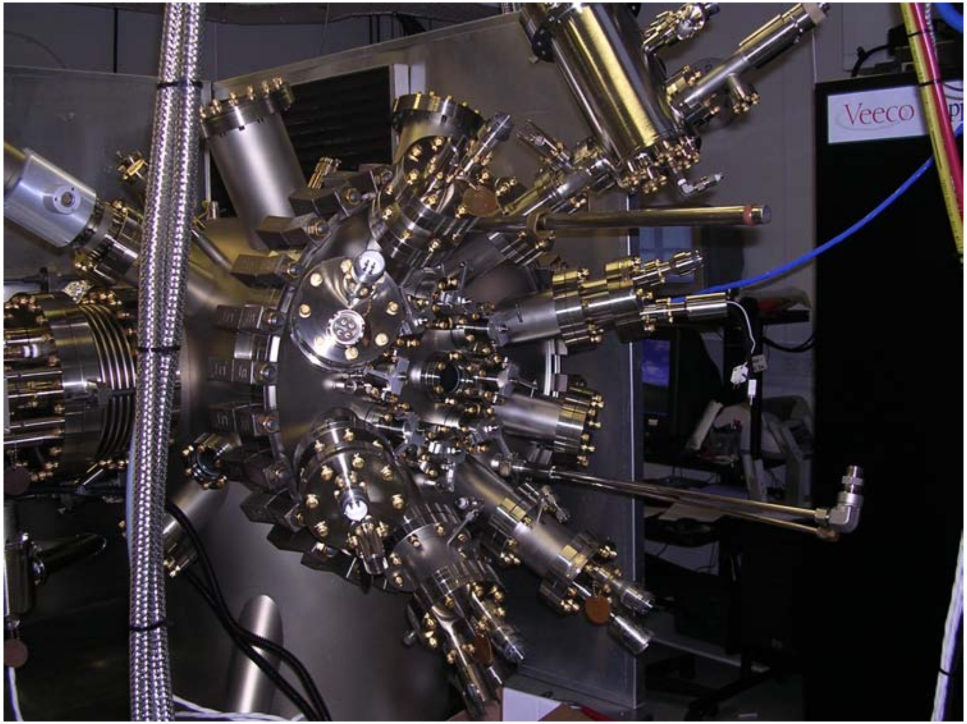
– extensive range of source materials

– layer thickness to monolayer accuracy

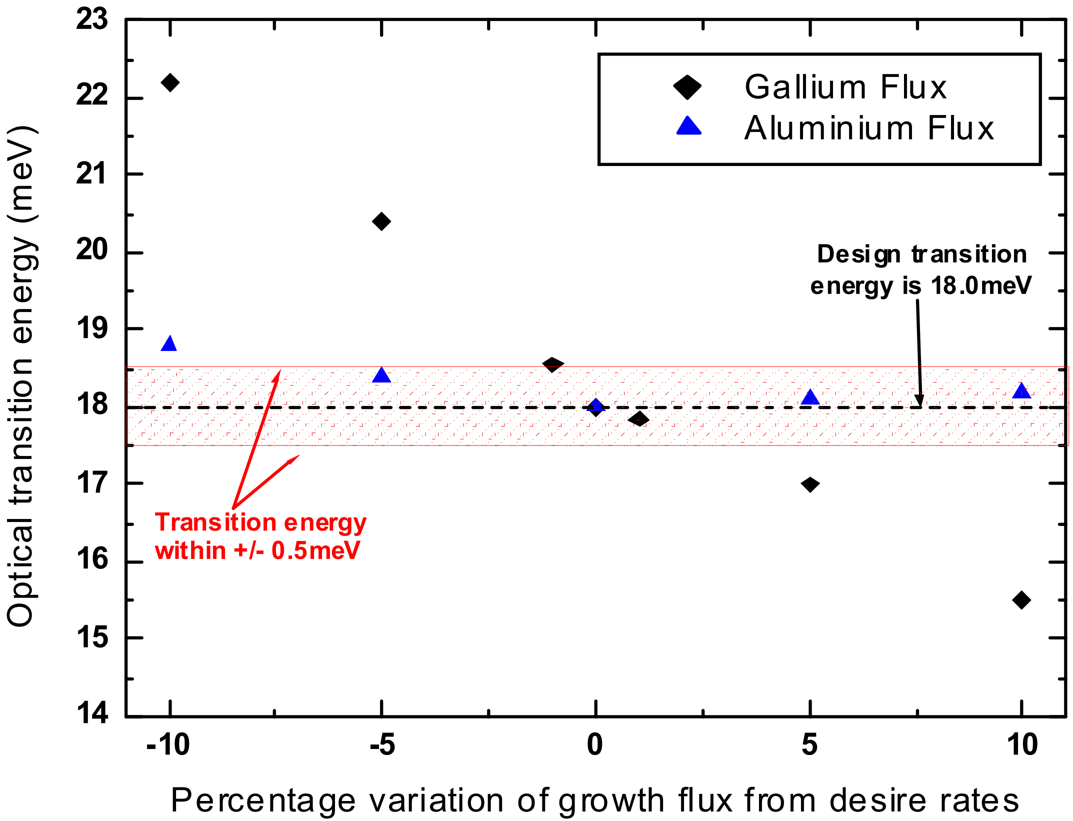
– high degree of control on layer composition & doping level

– abrupt interfaces

– little interface diffusion



Theoretical growth rate tolerances

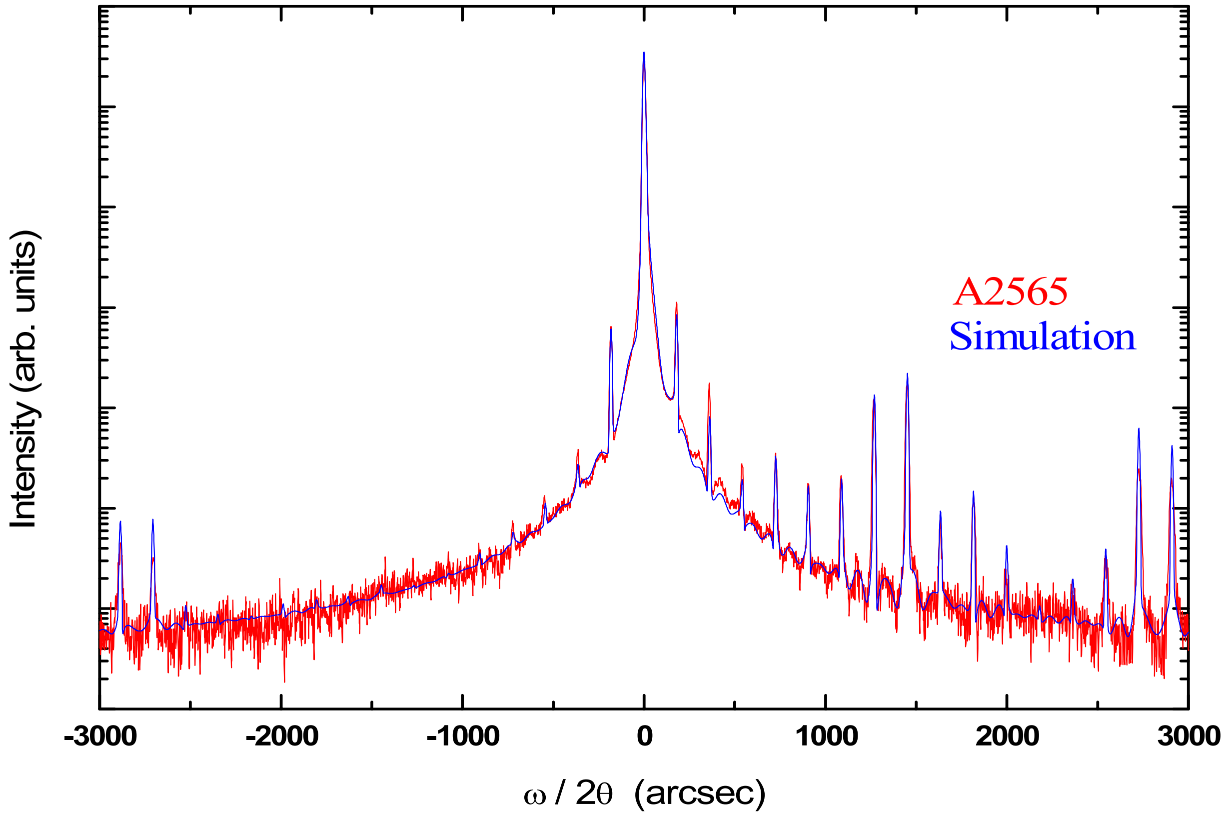


GaAs growth rate within +2% and –1%

AlAs growth rate within +10% and –5%

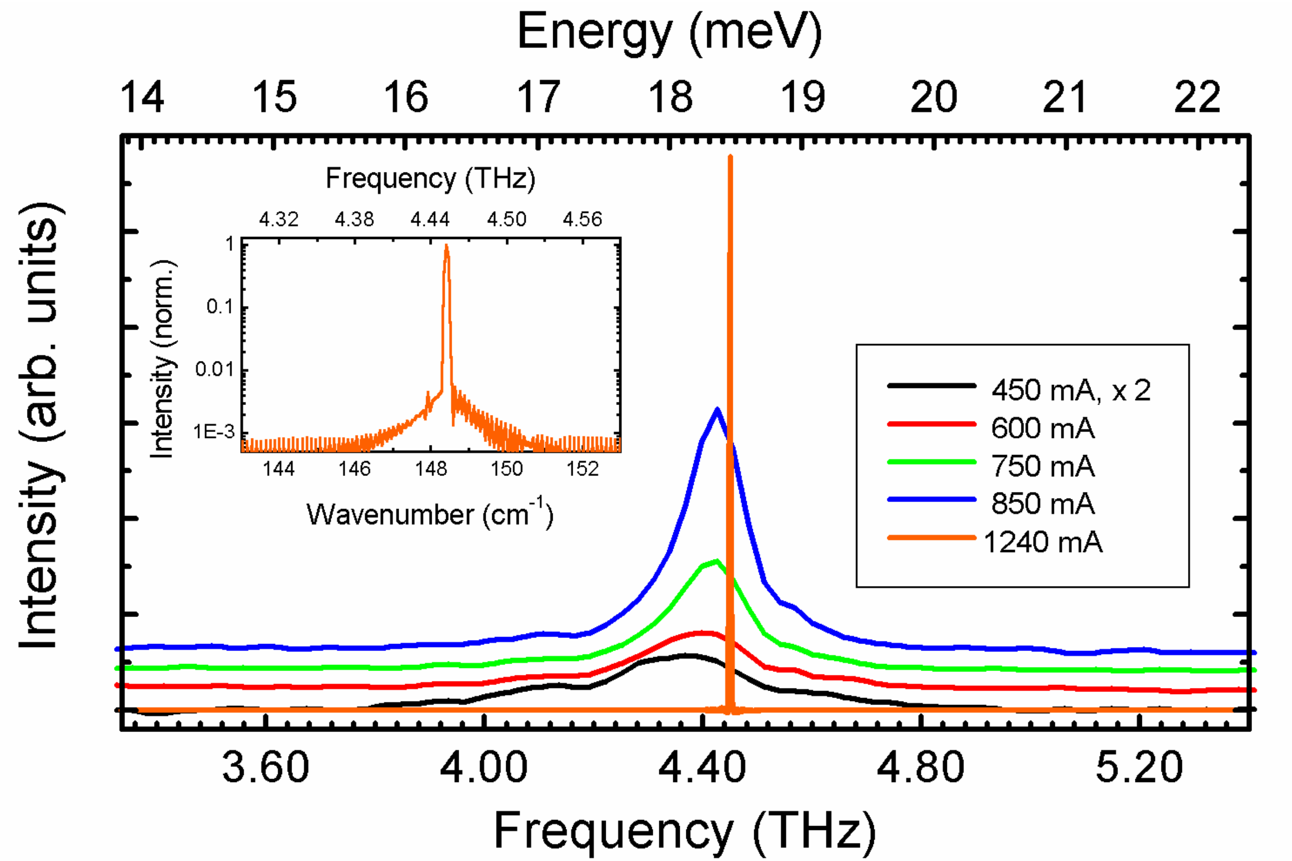
Beere *et al.*, J Cryst Growth **278**, p756 (2005)

X-ray spectra of THz laser



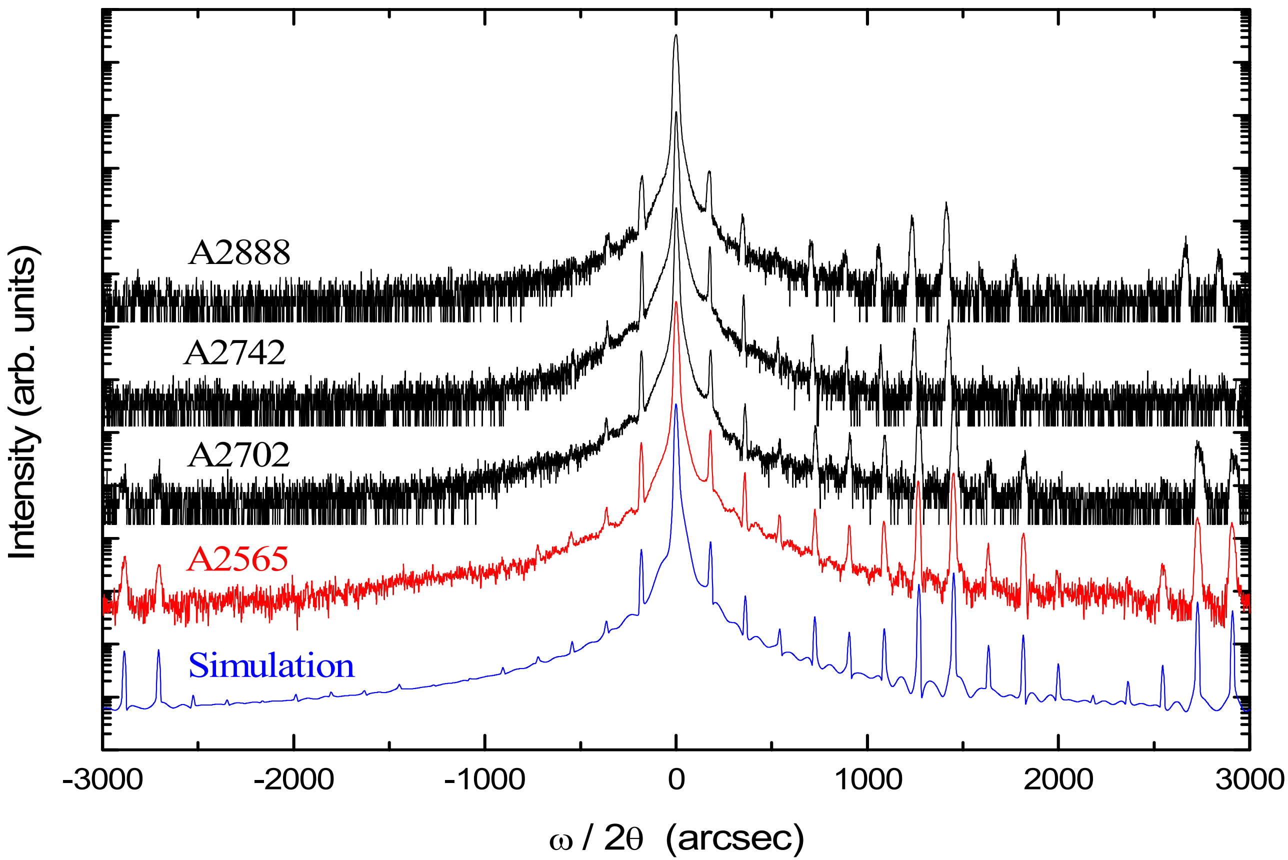
- Clear satellite structure in good agreement with simulation
- Confirms excellent growth stability over 12 hour growth duration
- Thickness variation across 2” wafer is less than 2%

Terahertz Quantum Cascade Laser



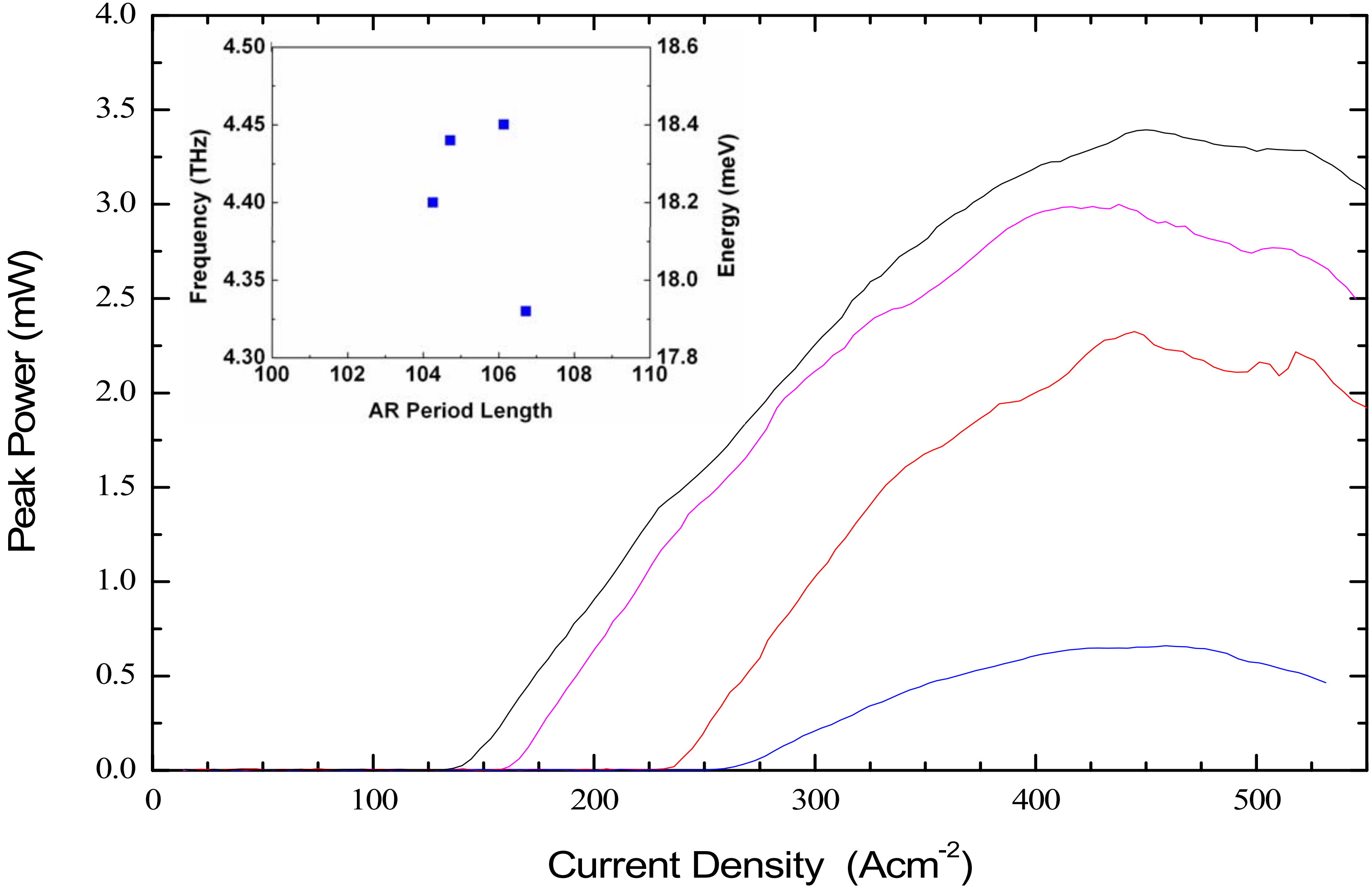
- Single-mode emission from a Fabry-Perot Cavity
- Emission at 18.4meV: 4.44THz - Good agreement with design

Structure Reproducibility



• Good agreement design thickness and measured value (-1% to +2%)

Structure Reproducibility

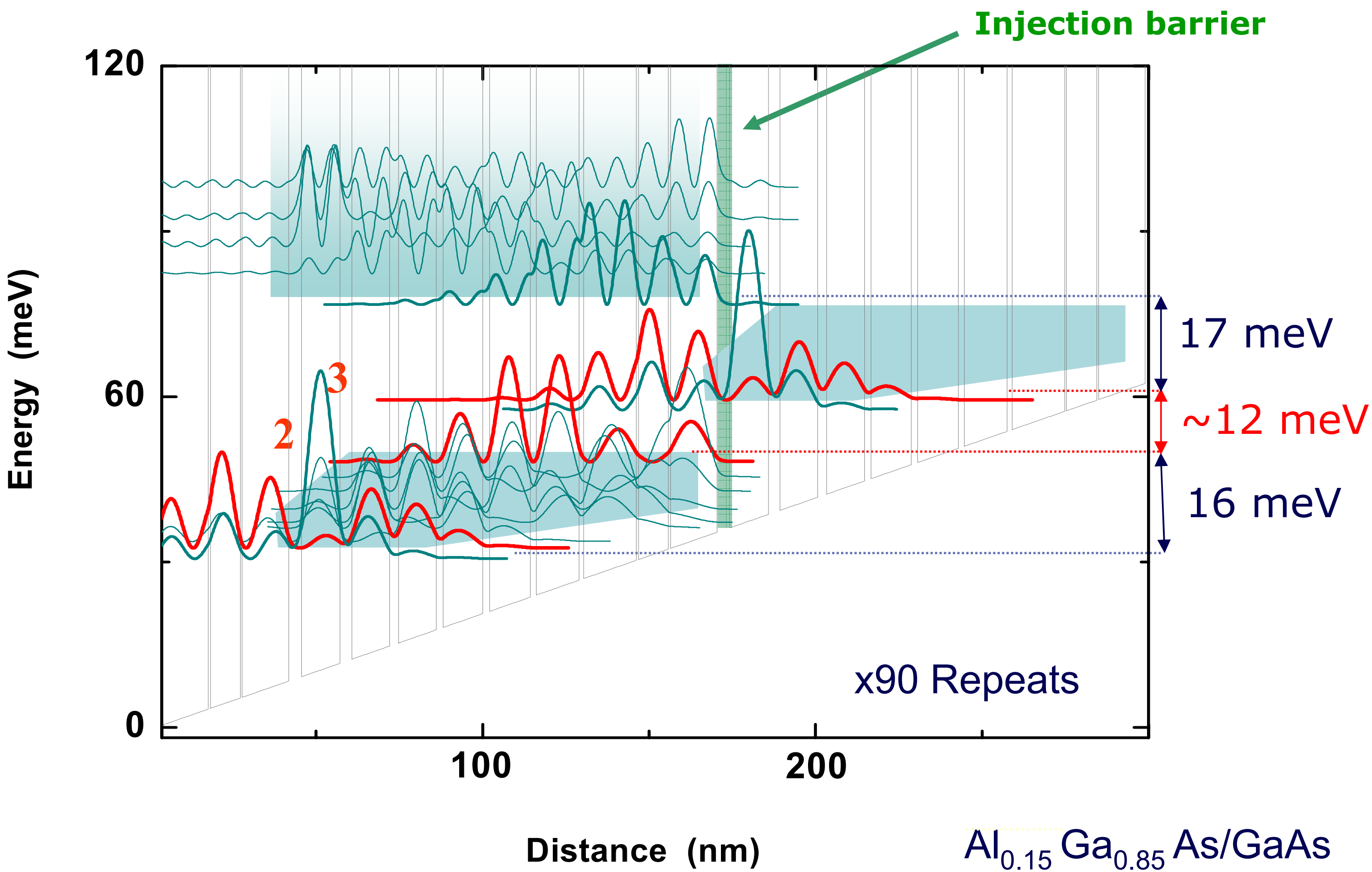


- Single-mode emission from a Fabry-Perot Cavity
- Emission at ~18.2meV: 4.4THz - Good agreement with design

Robustness of Active Region Design

Barbieri *et al.*, APL, vol. 85, p1674 (2004)

2.9 THz bound-to-continuum QCL AR



$Al_{0.15}Ga_{0.85}As/GaAs$

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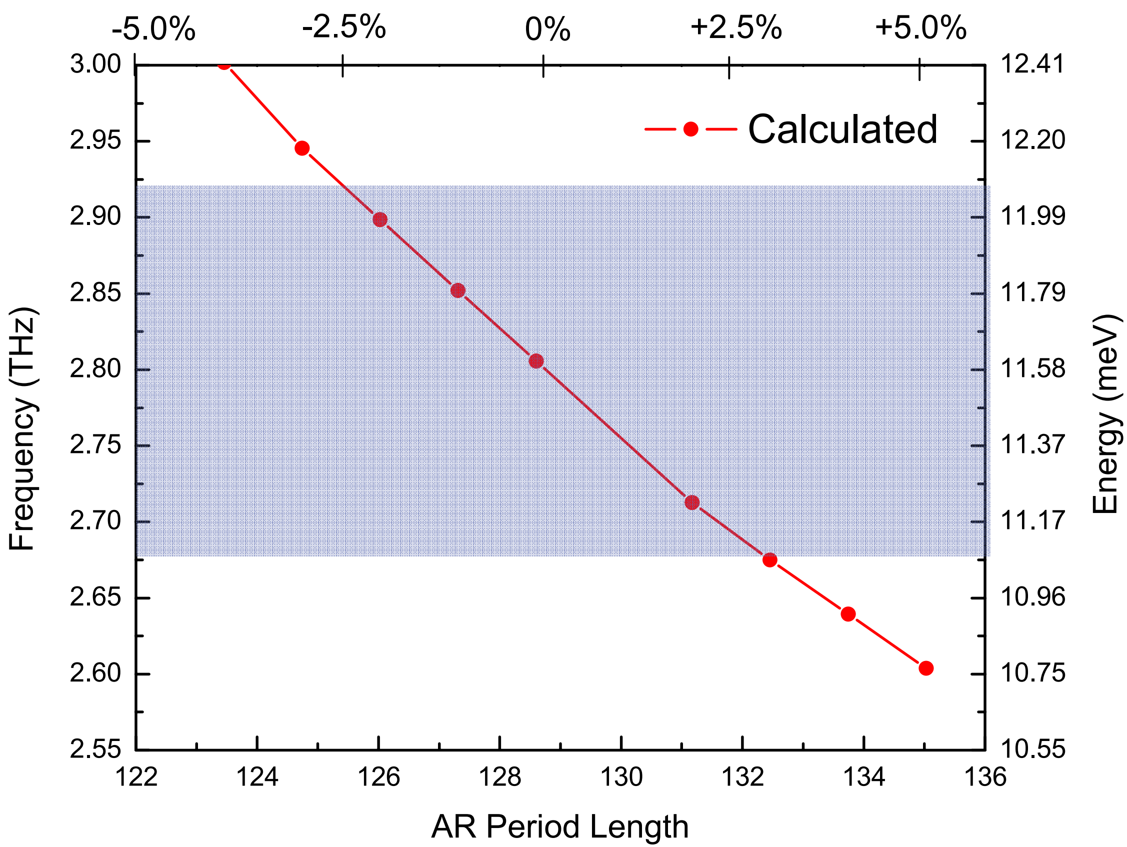
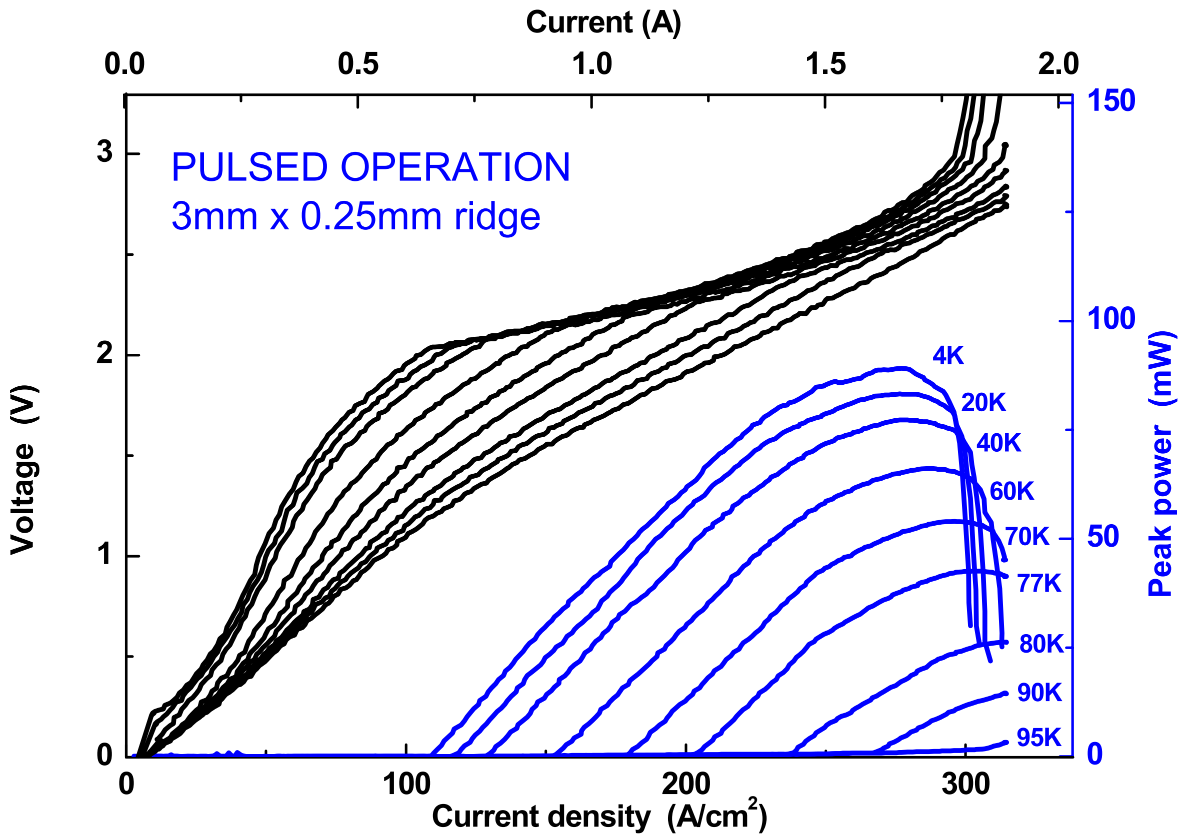
Active Region Robustness



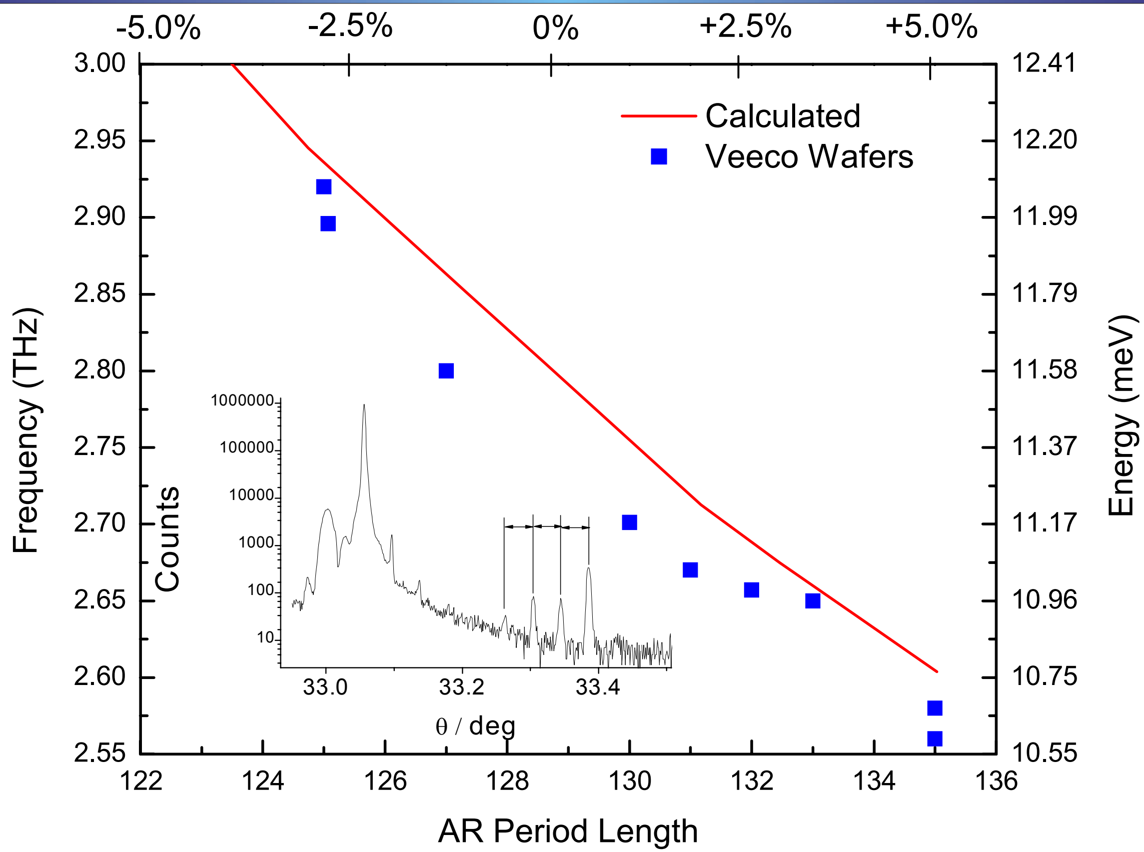
- Calculated emission frequency vs total AR thickness
- Again ±0.5meV emission energy equates ~ ±2% thickness

Active Region Robustness



- Single plasmon waveguide V_{align} ~2v: T_{max} ~95K: P_{max} ~90mW
- Series structure growths -5% to +5%

Active Region Robustness



- Actual range (-3%, +5%) ⇒ ~0.4THz (~2.5meV)
- Systematic route to tuning emission frequency
- Could possibly extend frequency range further (>5%)?

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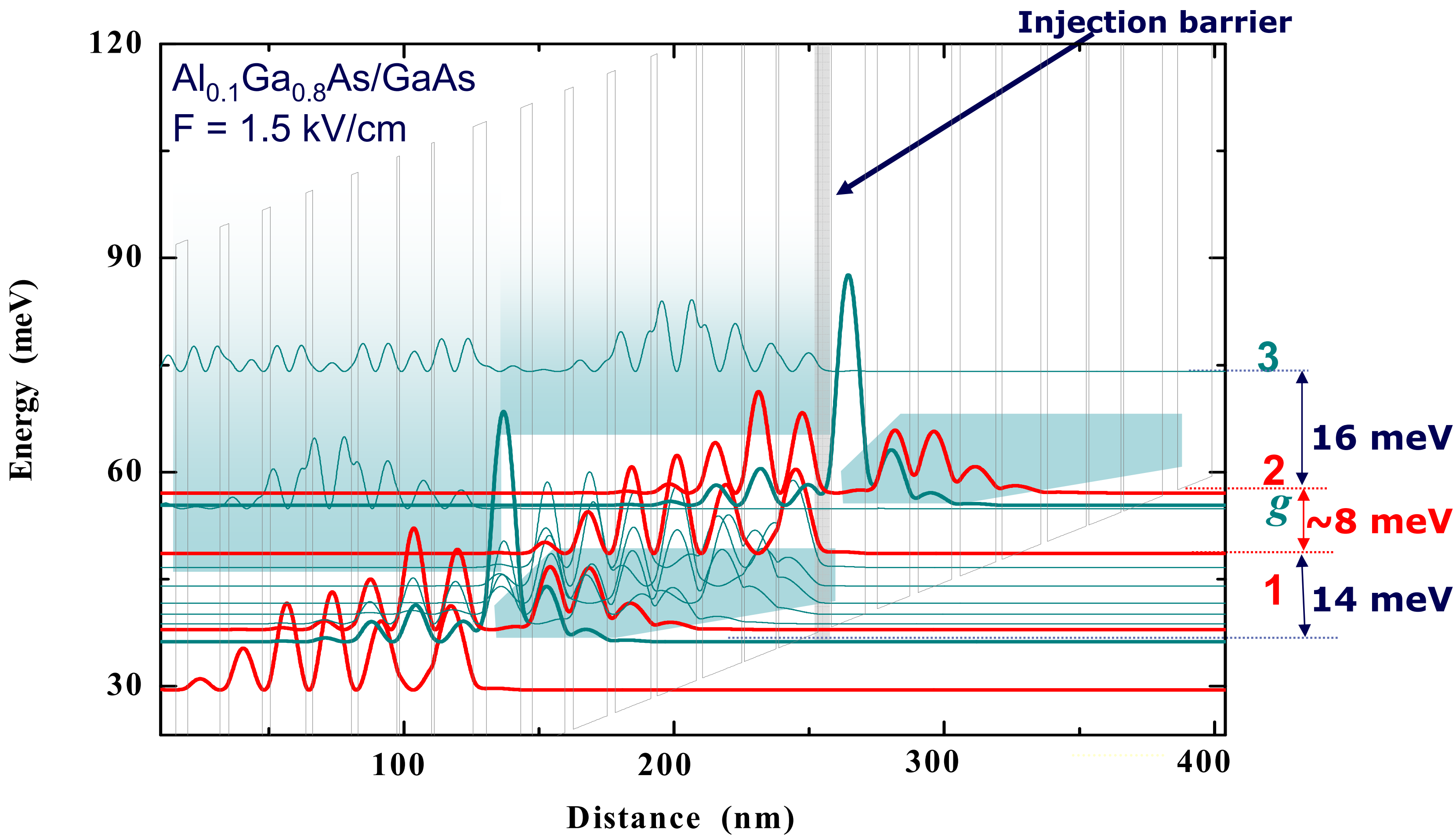
Active Region Robustness II

Worrall *et al.*, Optics Express, 14, 171 (2006)

2.0 THz bound-to-continuum QCL AR



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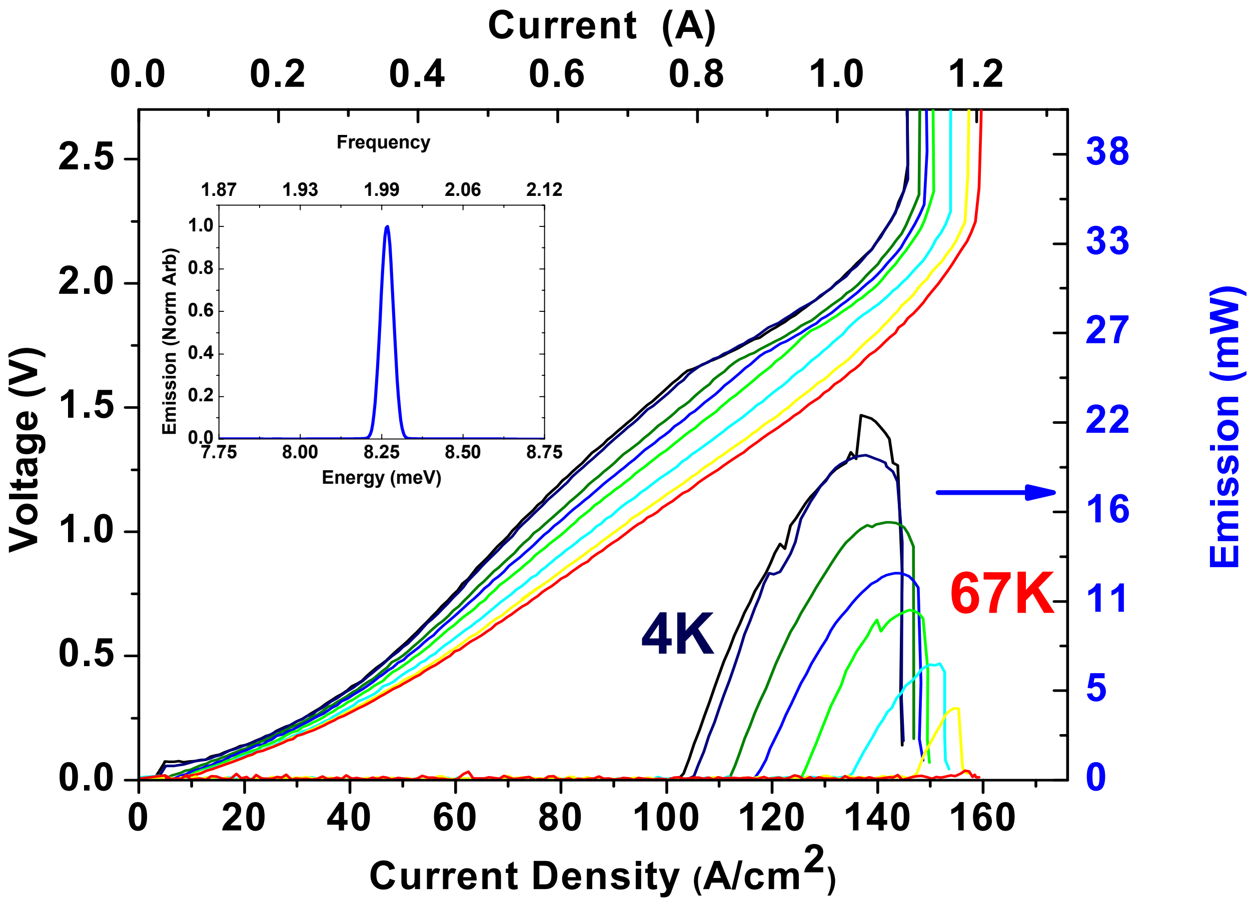
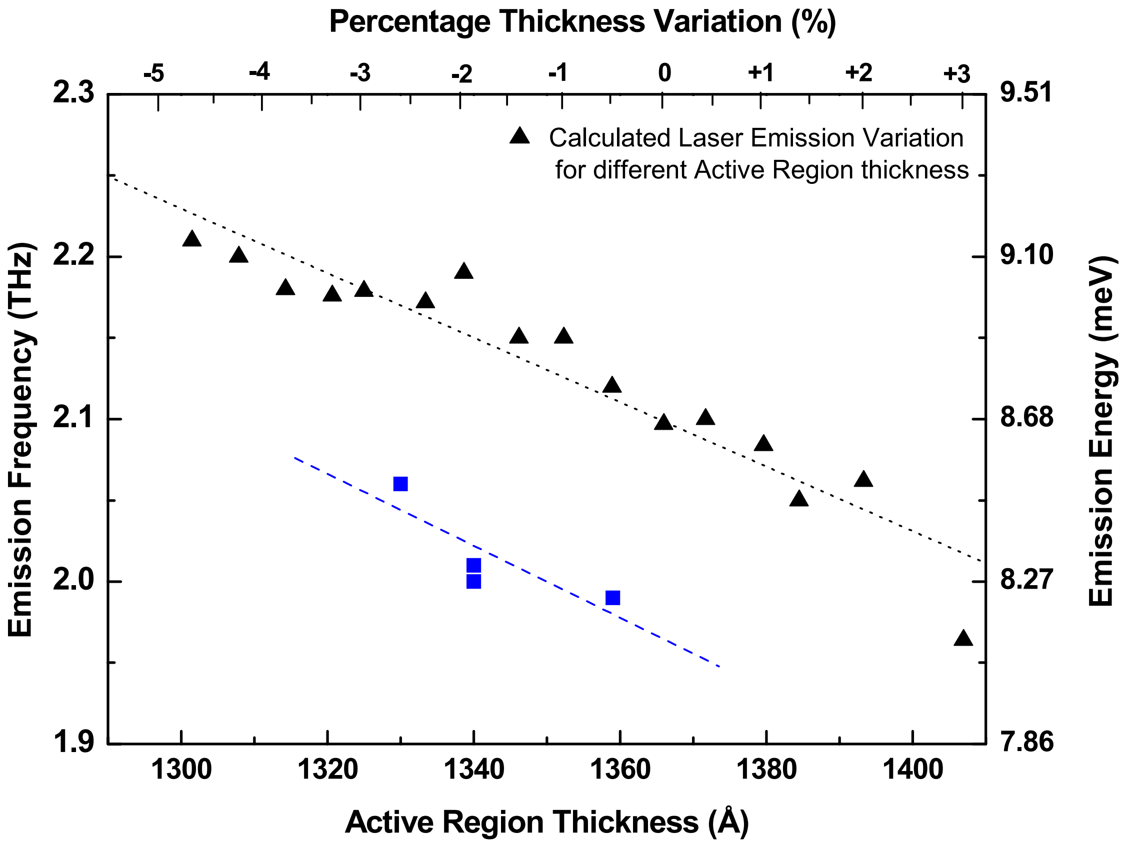
Active Region Robustness II



• Single plasmon waveguide 3mm x 0.25mm ridge waveguide

J_{th} 103 Acm^{-2} – V_{align} ~1.8v : T_{max} = 67K Output Power ~22mW f ~2.00THz

Active Region Robustness II



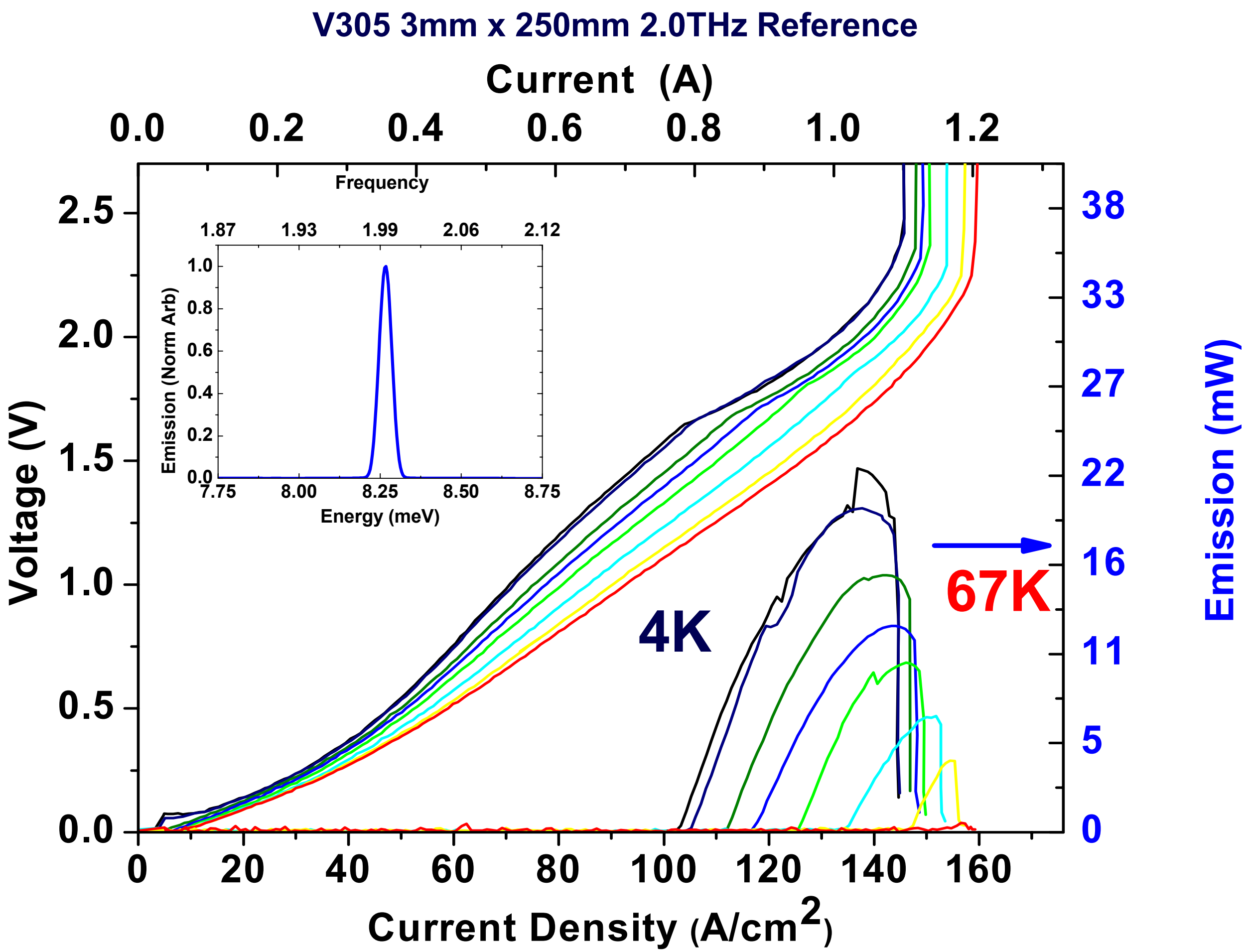
- Similar 'linear' trend emission frequency against AR thickness
- Limited range (~3%) explored to date ⇒ ~0.06THz span
- Investigate extending frequency further!

Active Region Robustness II

- **Bound-to-continuum design very robust!**
- **Possible systematic route to tuning frequency**

  how far can we realistically exploit this method?

Minor Structure Variations



J_{th} 103 Acm^{-2} – V_{align} ~1.8v : T_{max} = 67K Output Power ~22mW f ~2.00THz

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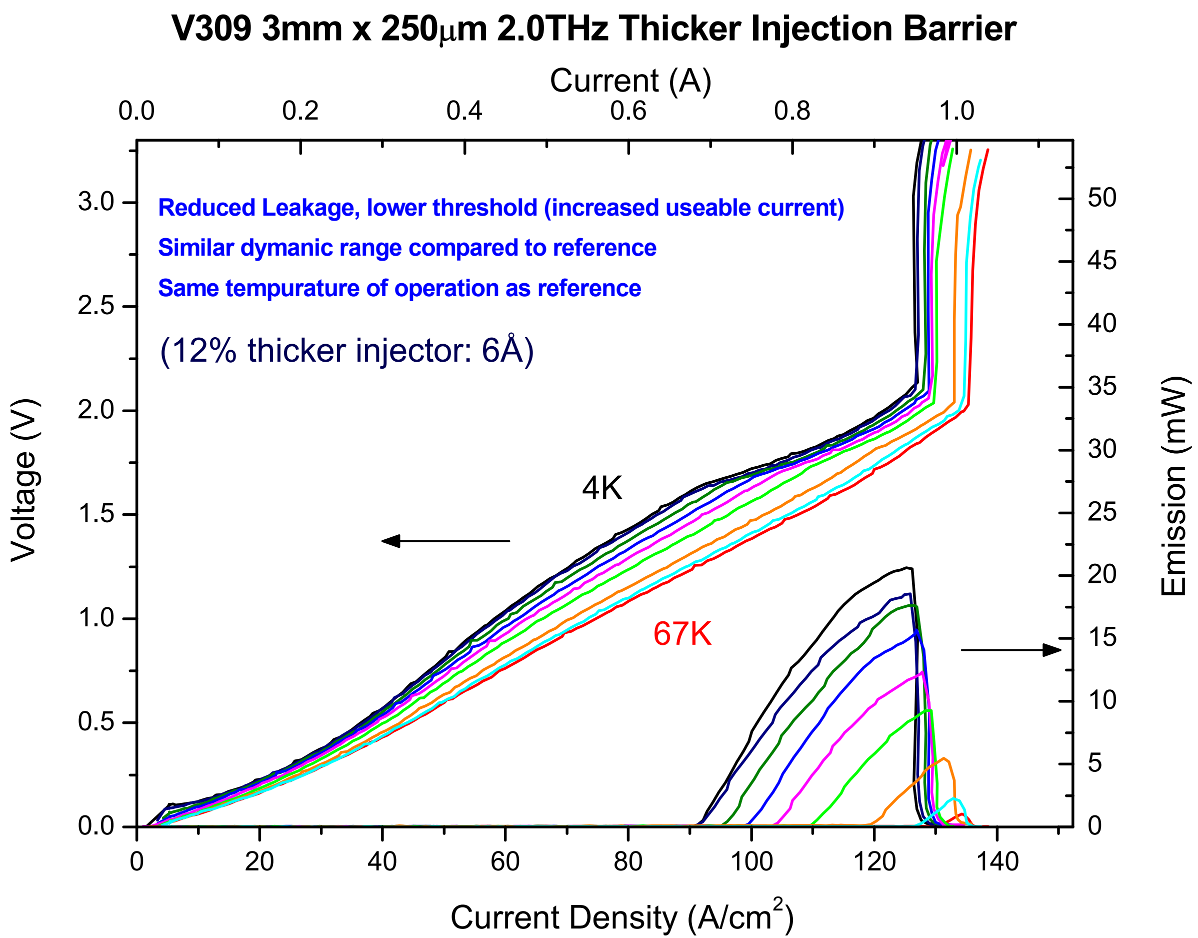
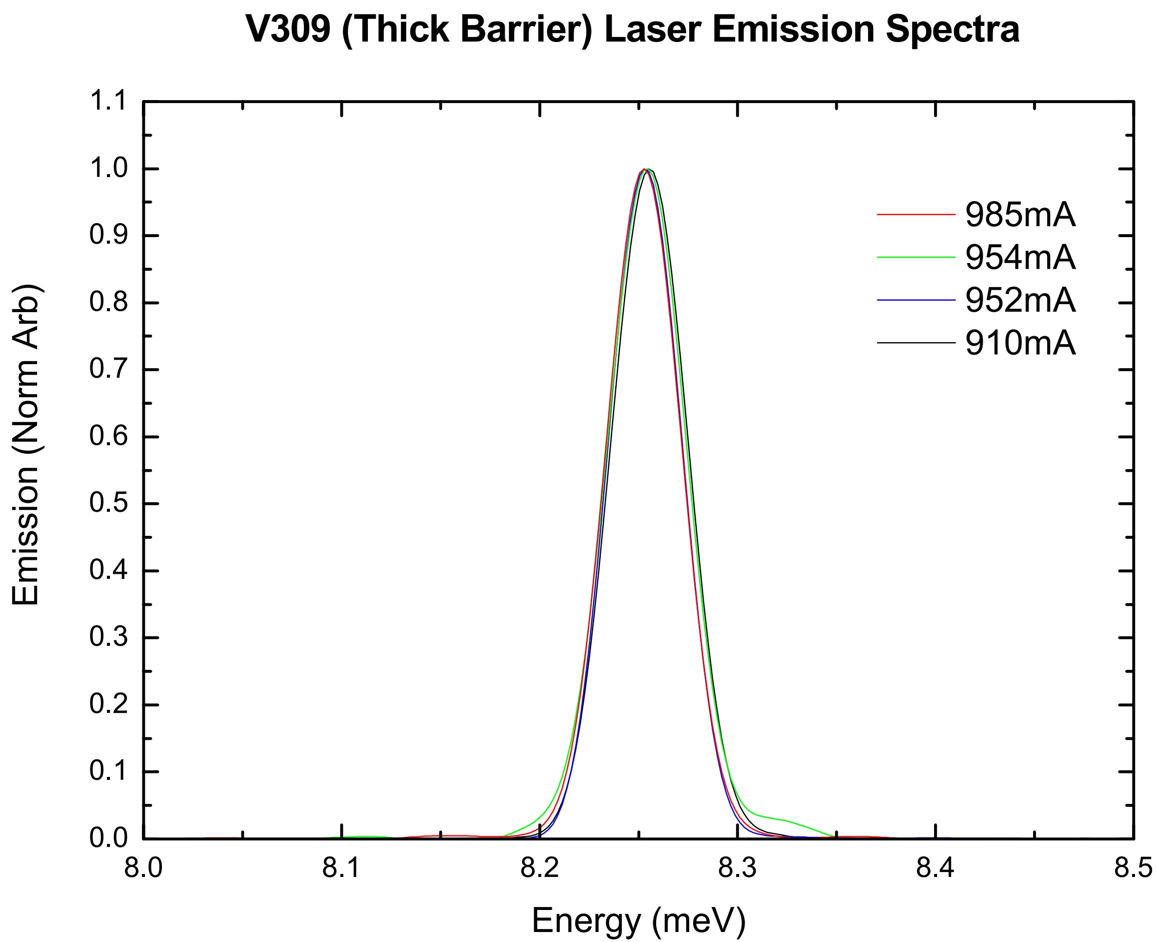
Minor Structure Variations



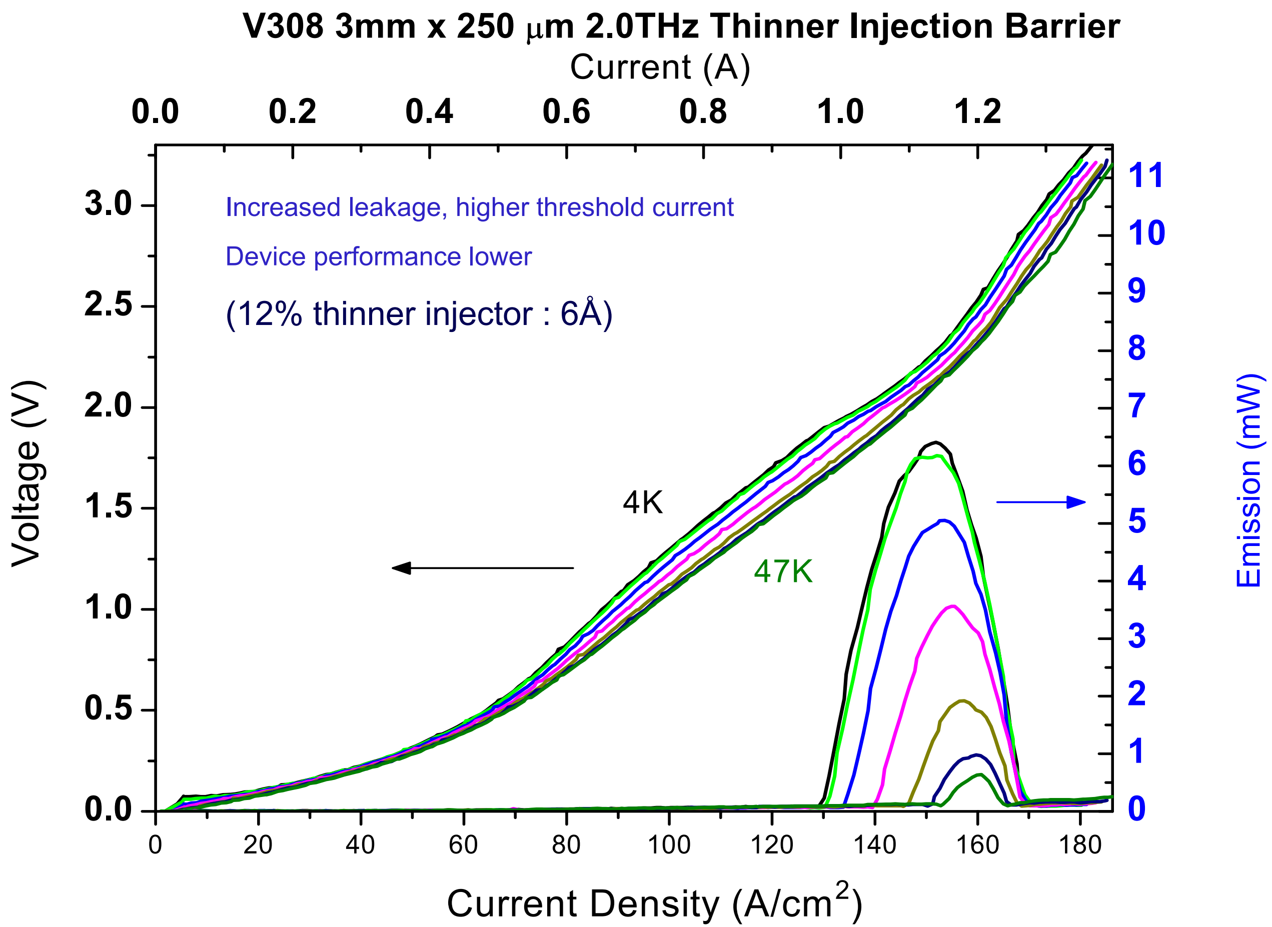
J_{th} 90 Acm^{-2} – V_{align} ~1.7v : T_{max} = 67K Output Power ~22mW

Minor Structure Variations



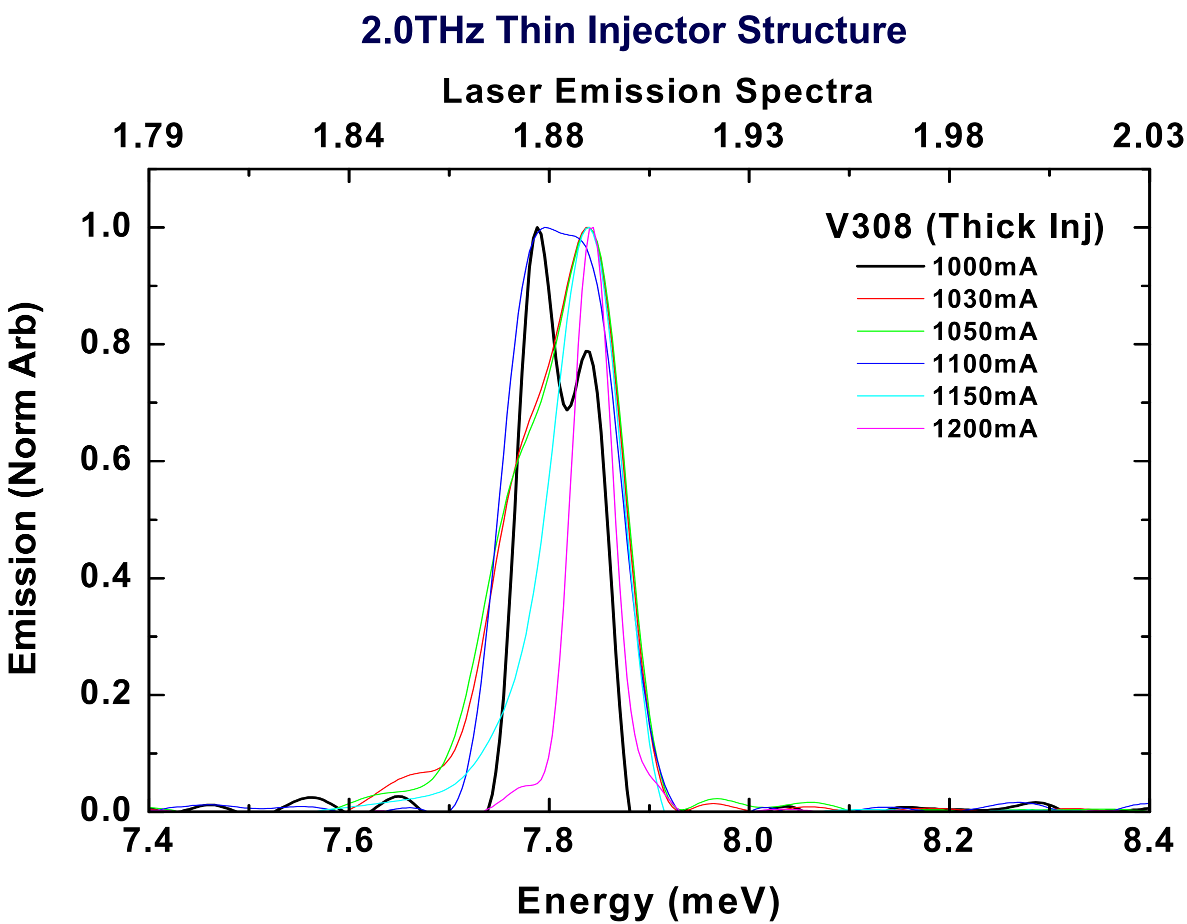
1.99THz (8.25meV) – Singlemode (Frequency identical to Reference)

Minor Structure Variations



J_{th} 133 Acm^{-2} (V_{align} ~1.9A): T_{max} = 47K Output Power ~7mW

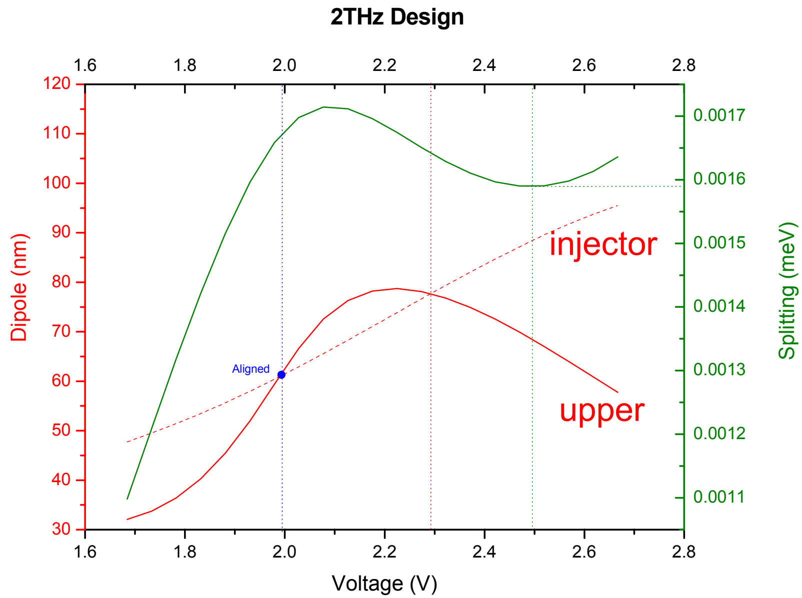
Minor Structure Variations

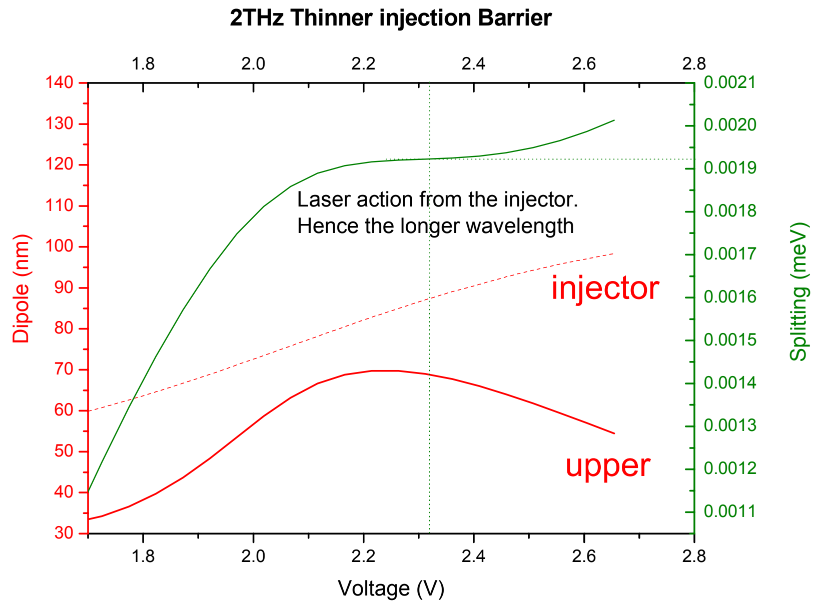


1.88THz (7.79meV) – lower frequency compared 2.0THz reference

Minor Structure Variations

Overlap strength between lower state and upper, injector

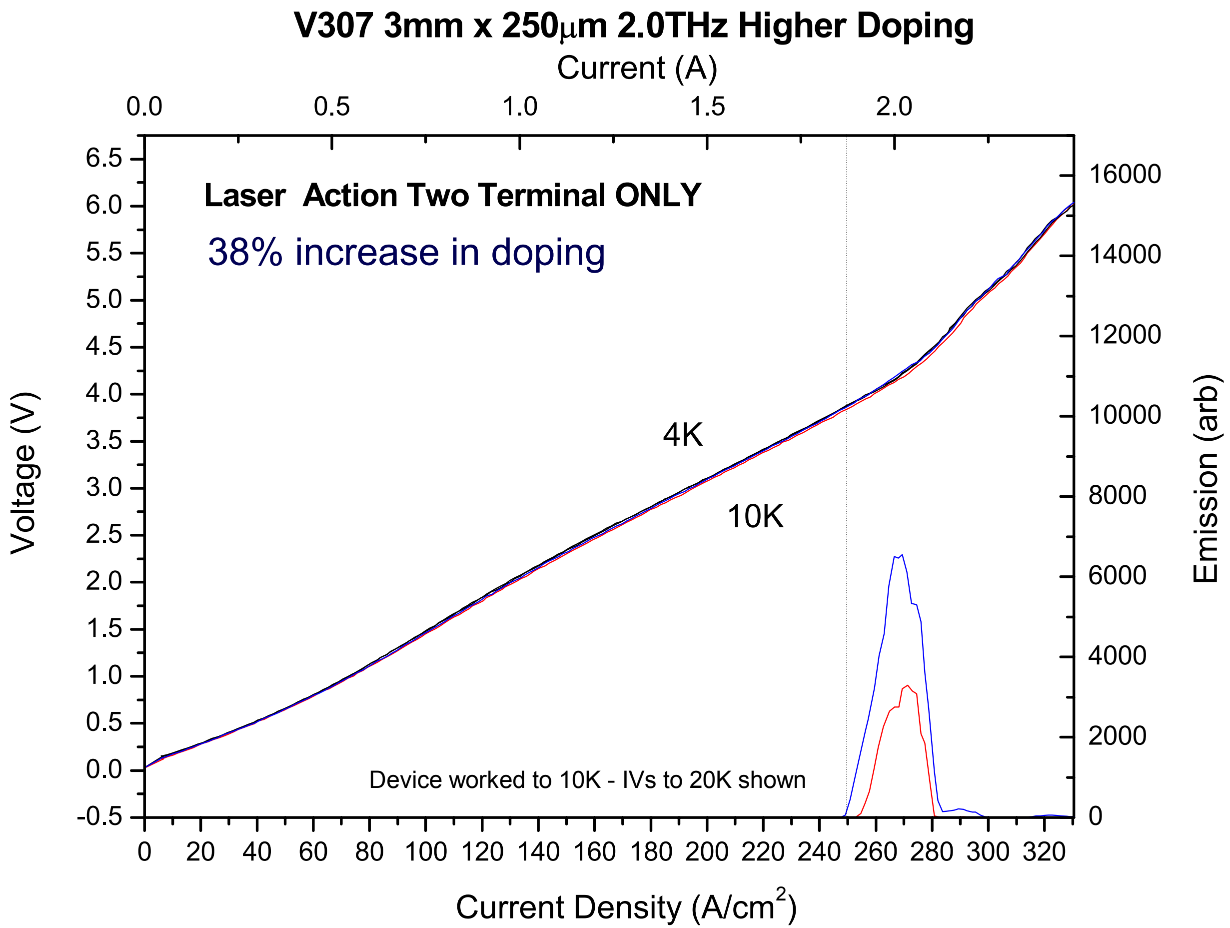




Thinner injector barrier no longer produces isolated upper and injector states

STRUCTURE LASES FROM INJECTOR TO LOWER STATE ⇒ LOWER FREQUENCY

Minor Structure Variations



- Device operation severely degraded

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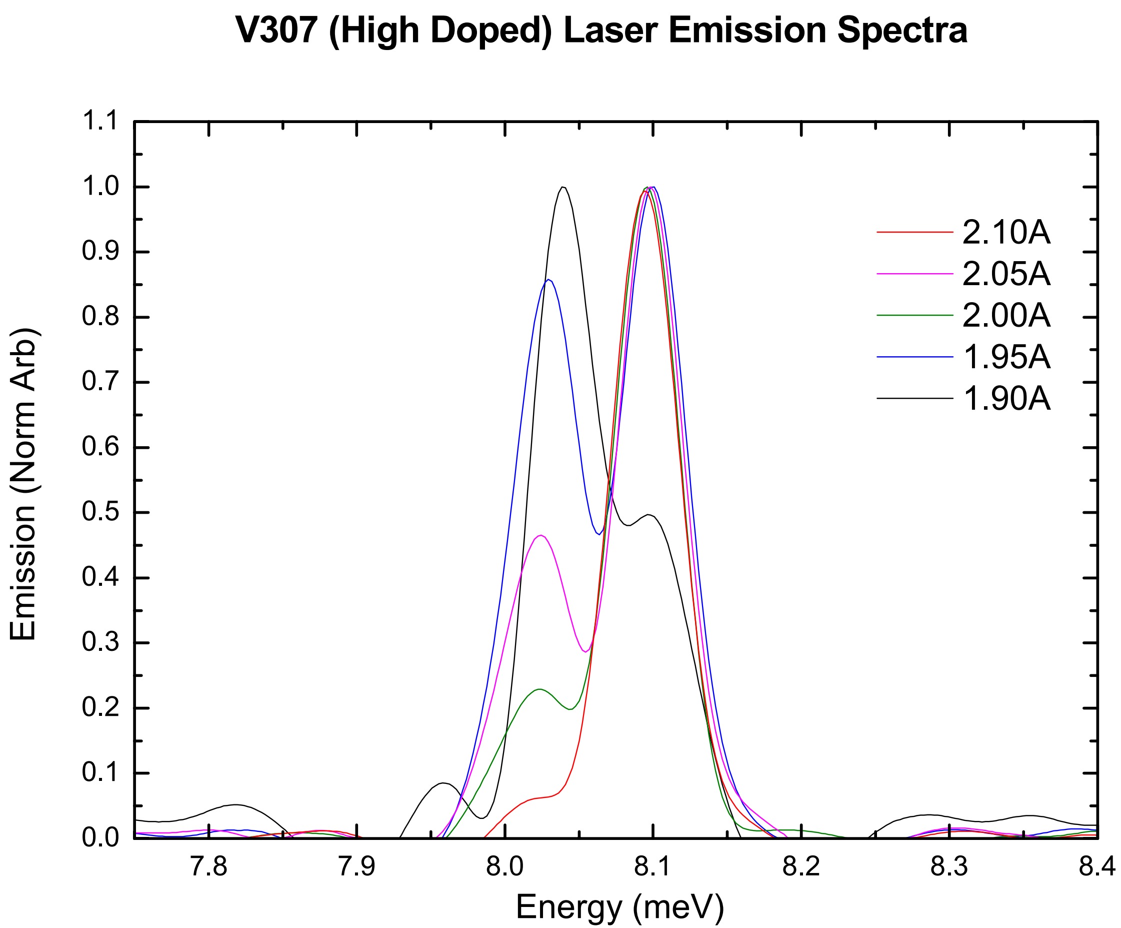
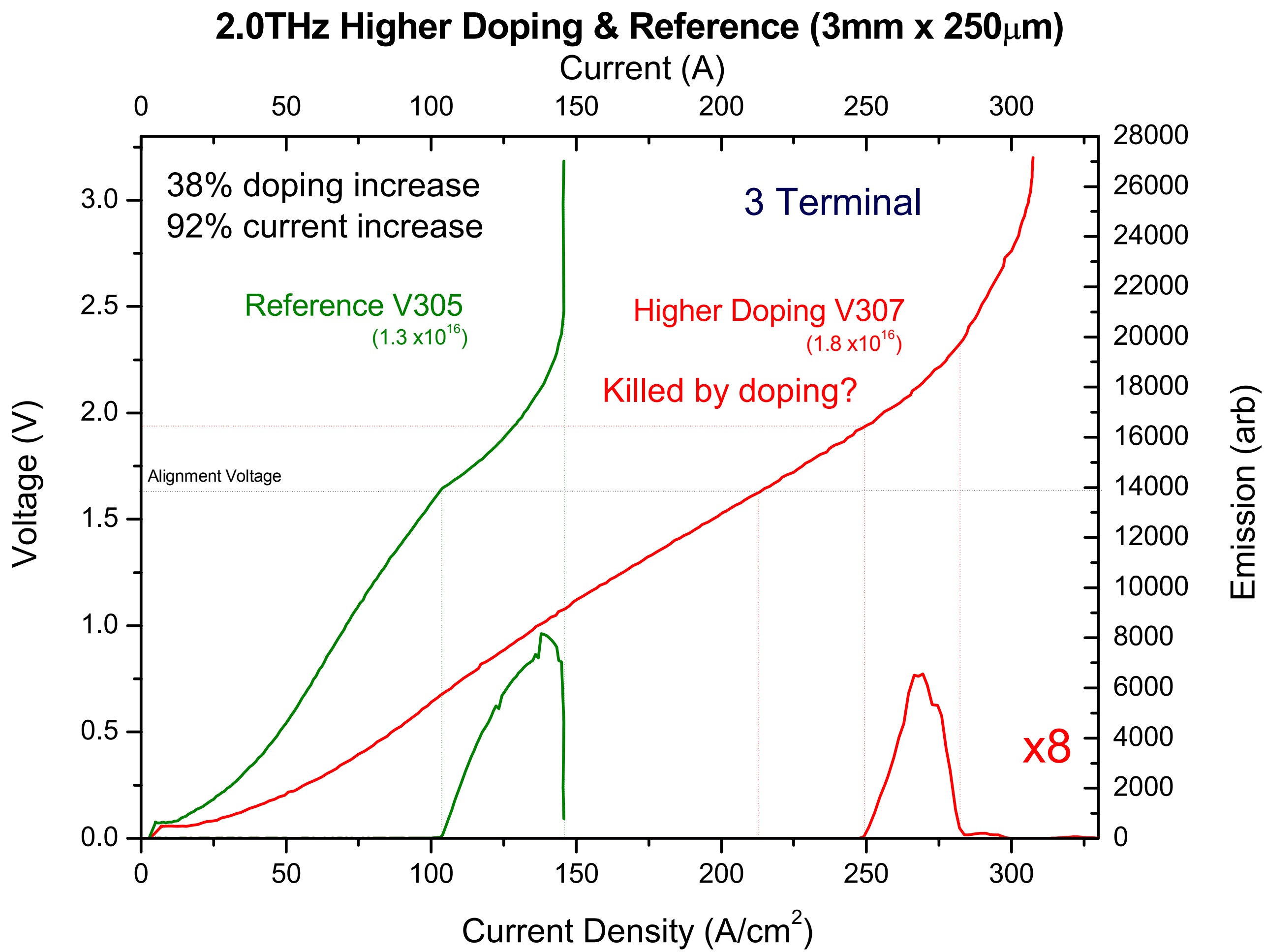
Minor Structure Variations



1.94THz (8.04meV) – Multimode: just above threshold

1.96THz (8.10meV) – Multimode: just before NDR

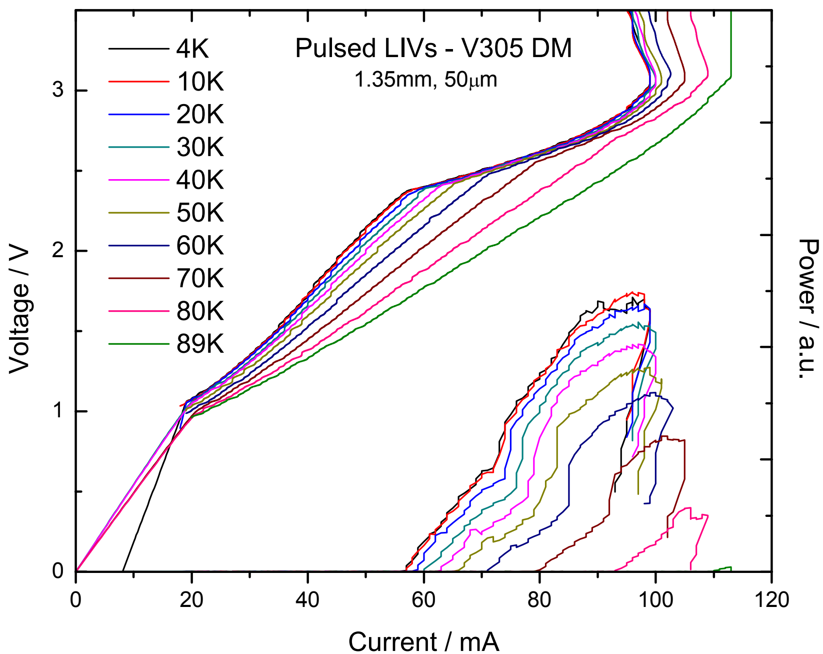
Minor Structure Variations

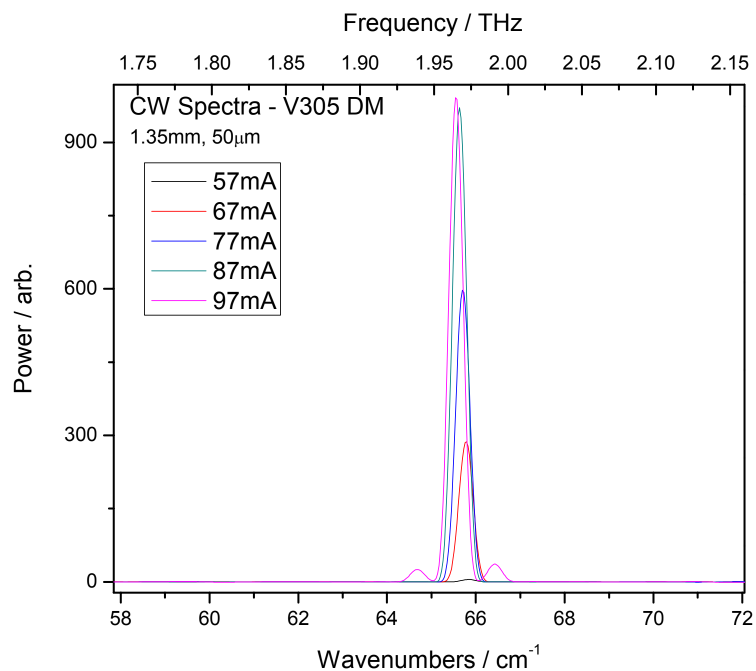


- Higher current kills device operation

Minor Structure Variations

2THz Reference (V305) double-metal THz QCL devices





T_{max} = 89K

1350 μm x 50 μm device

- Single plasmon waveguide T_{max} ~67K

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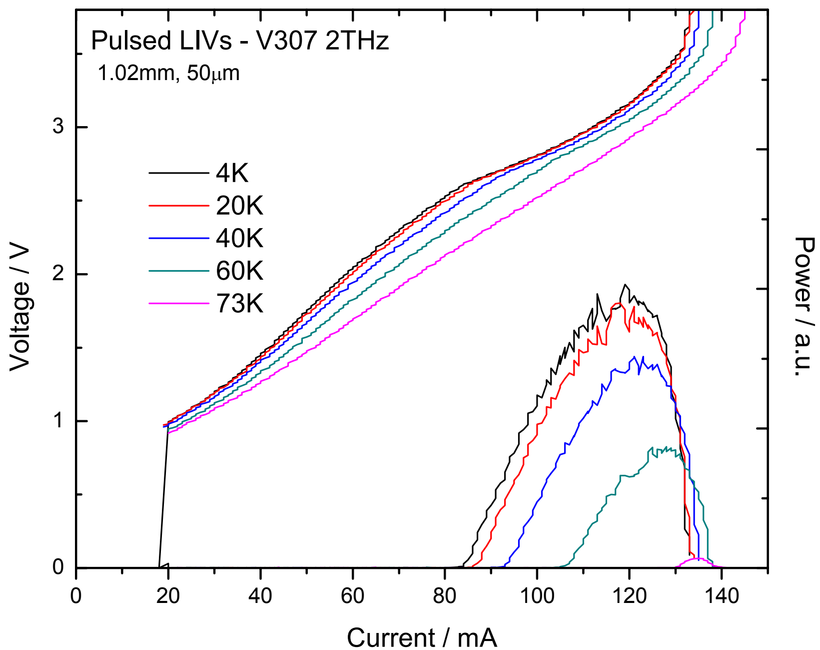
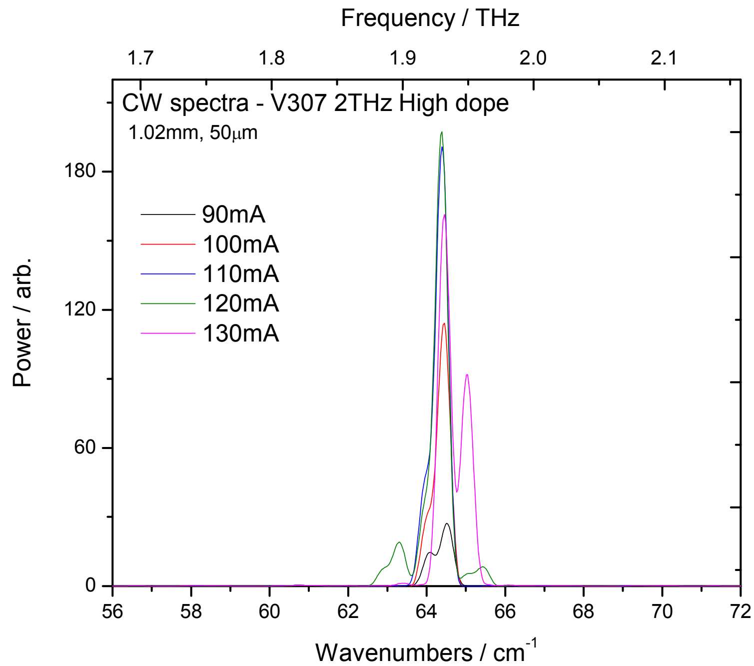
Minor Structure Variations

High doping (V307) double-metal THz QCL devices





T_{max} = 73K

1000 μm x 50 μm device

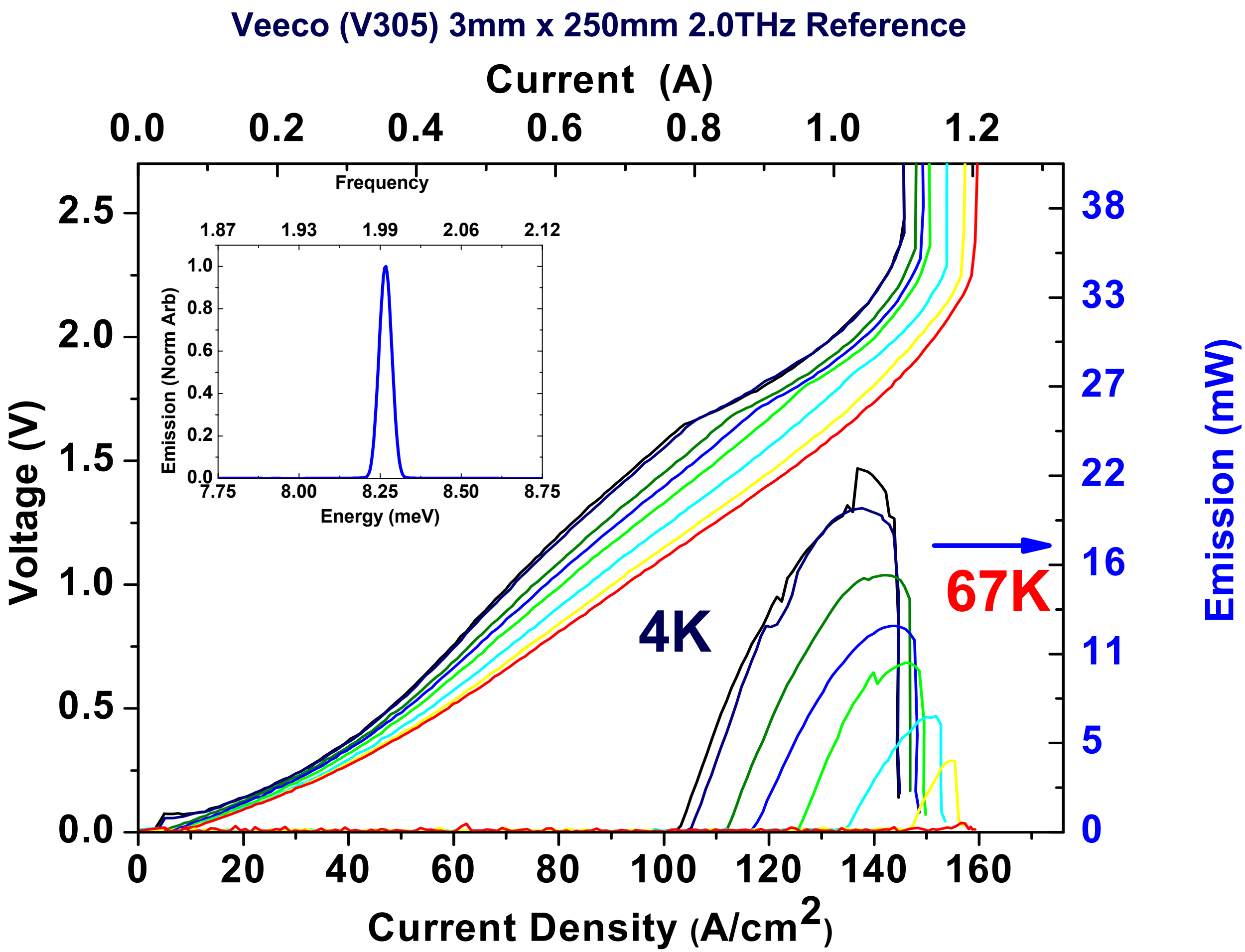
- Slightly degraded performance compared to single plasmon

Minor Structure Variations

- **QCL performance sensitive to structure**
  - *doping level critical (especially single plasmon waveguide)*
  - *ensure variations does not completely change design*

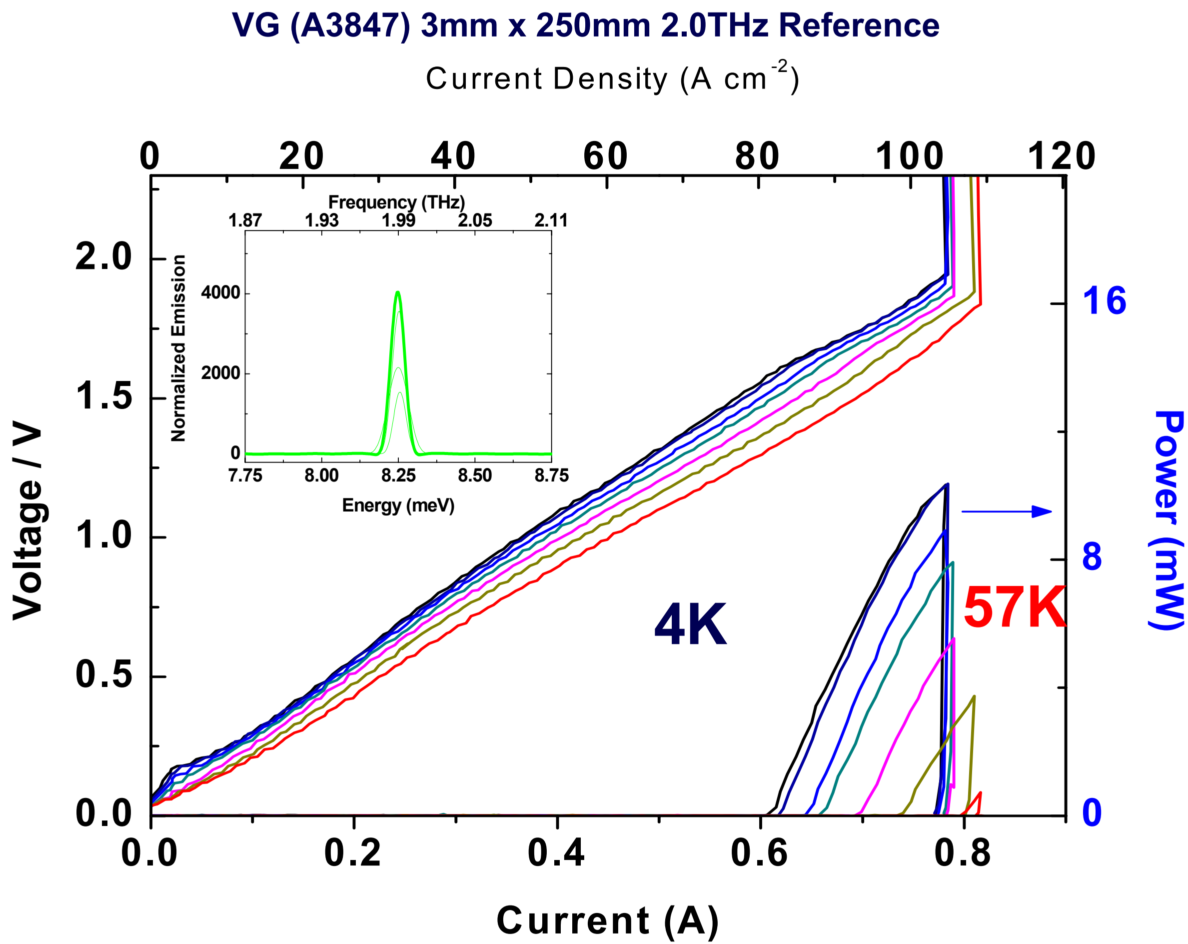
- **Growth needs to be accurate!**

Transfer of QCLs between growth systems



J_{th} 103 Acm^{-2} – V_{align} ~1.8v : T_{max} = 67K Output Power ~22mW f ~2.00THz

Transfer of QCLs between growth systems



J_{th} 82 Acm^{-2} – V_{align} ~1.6v : T_{max} = 57K Output Power ~10mW f ~1.99THz

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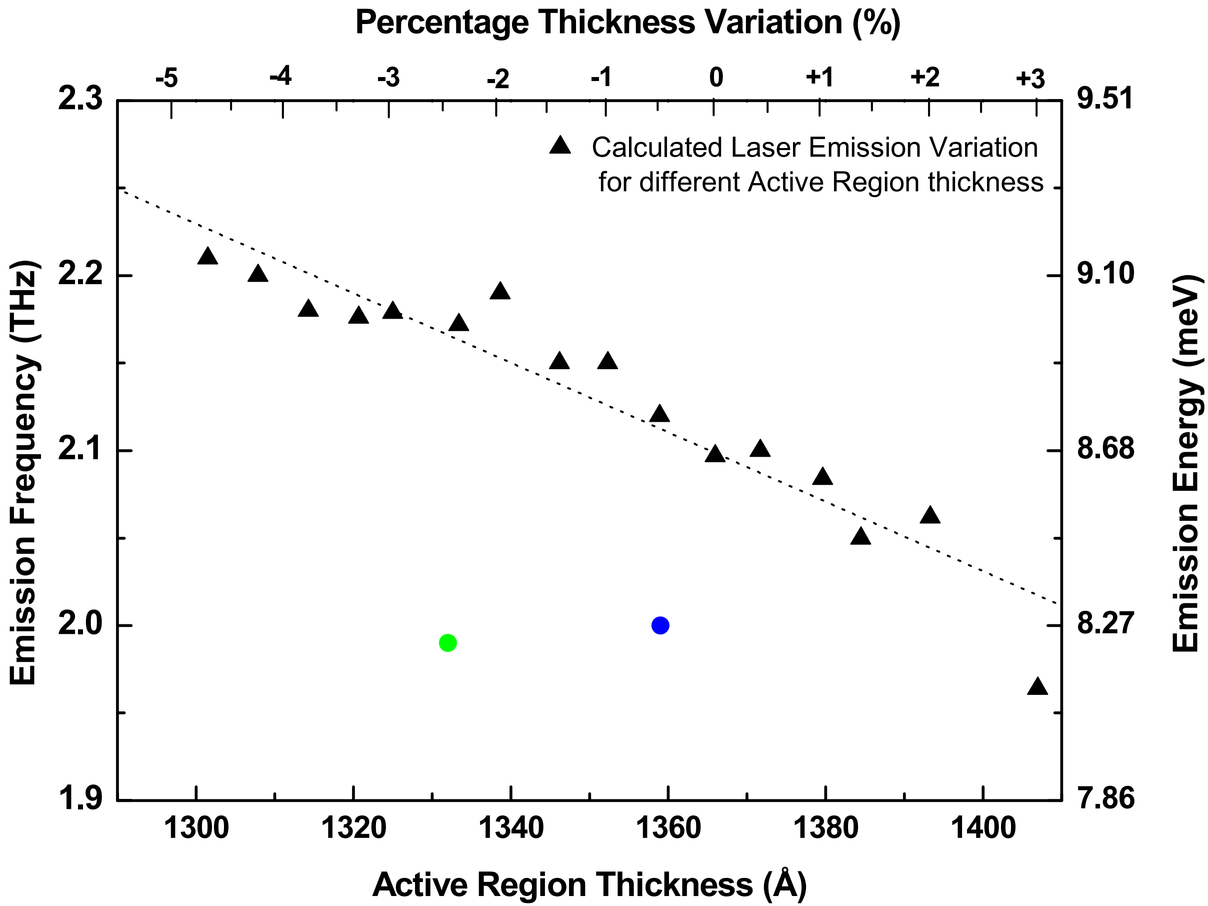
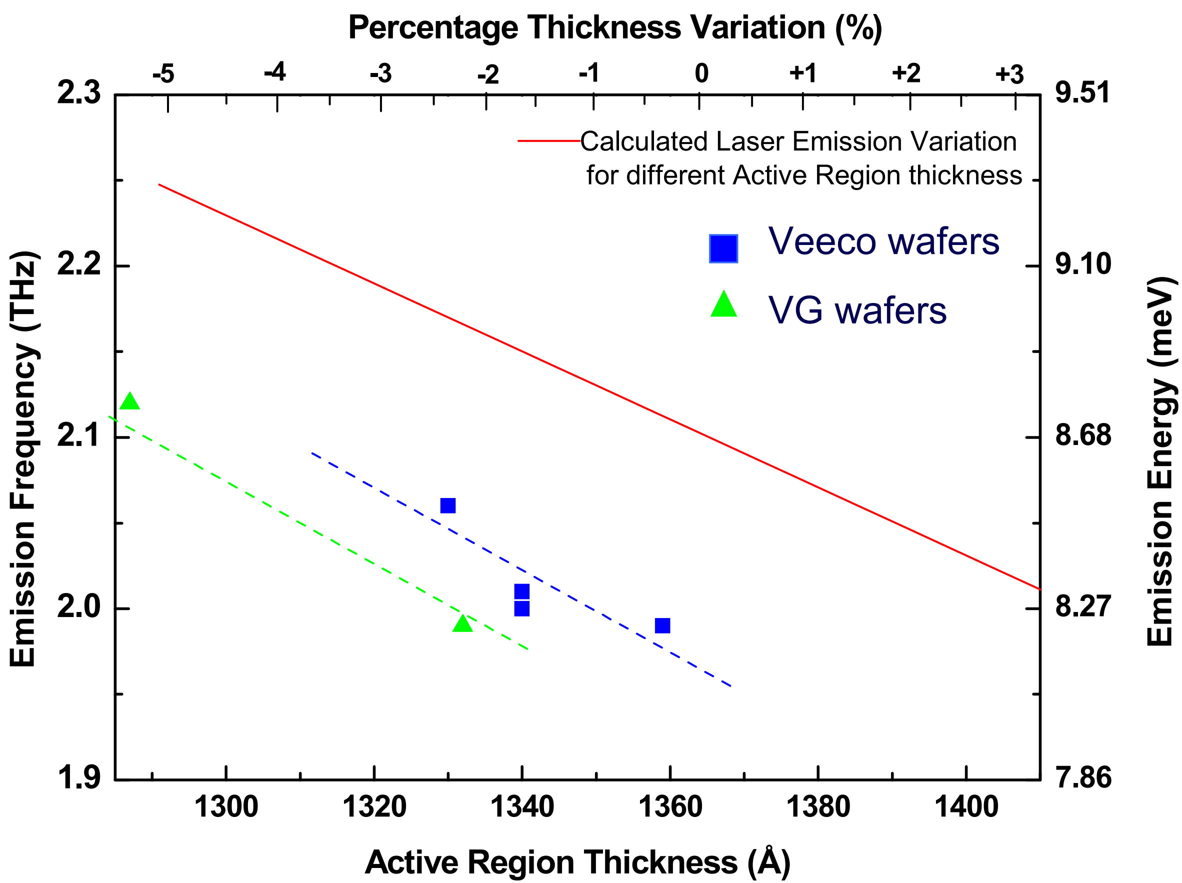
Transfer of QCLs between growth systems



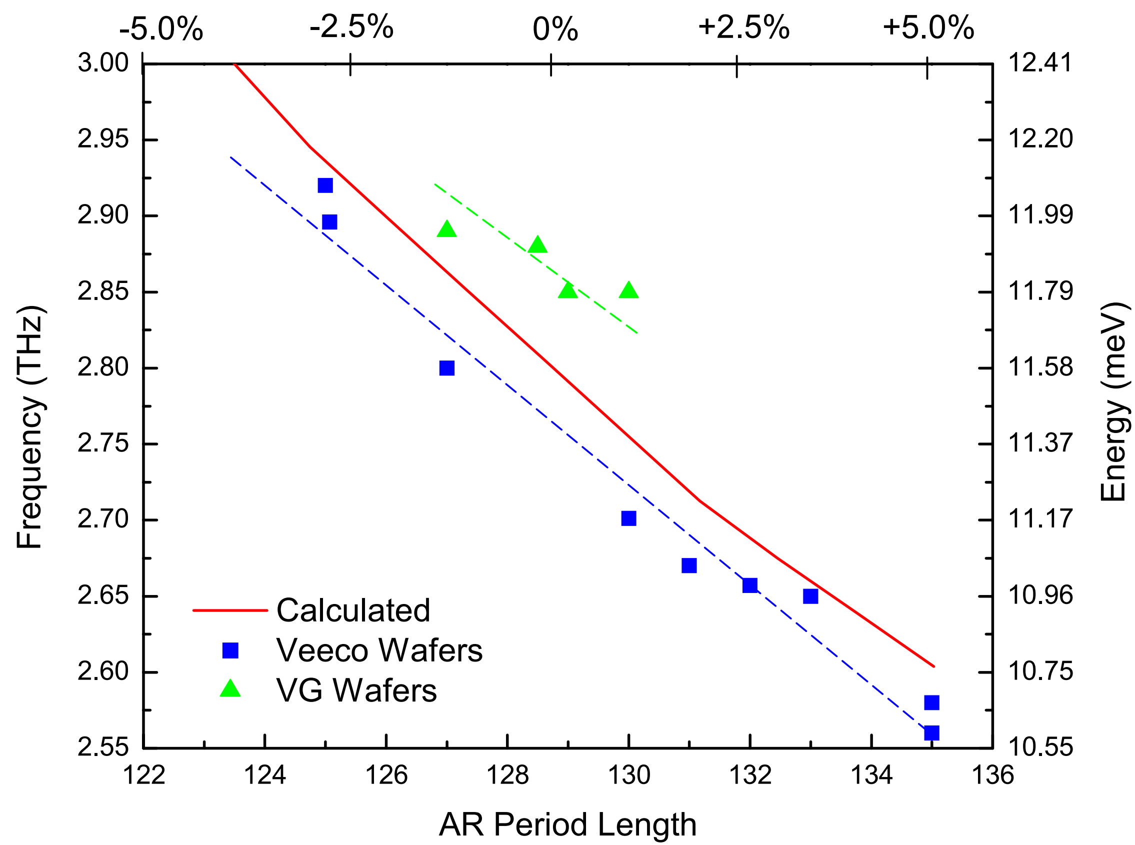
- Active regions different by 27Å (~2%) ⇒ 0.05THz
- Variation due to growth or fabrication?

Transfer of QCLs between growth systems



- VG wafers consistently lower frequency (~0.05THz)

Transfer of QCLs between growth systems



- VG wafers consistently higher frequency (~0.1THz)
- Observed frequency differences – *Barrier profile/thickness*
  – *Growth interfaces*

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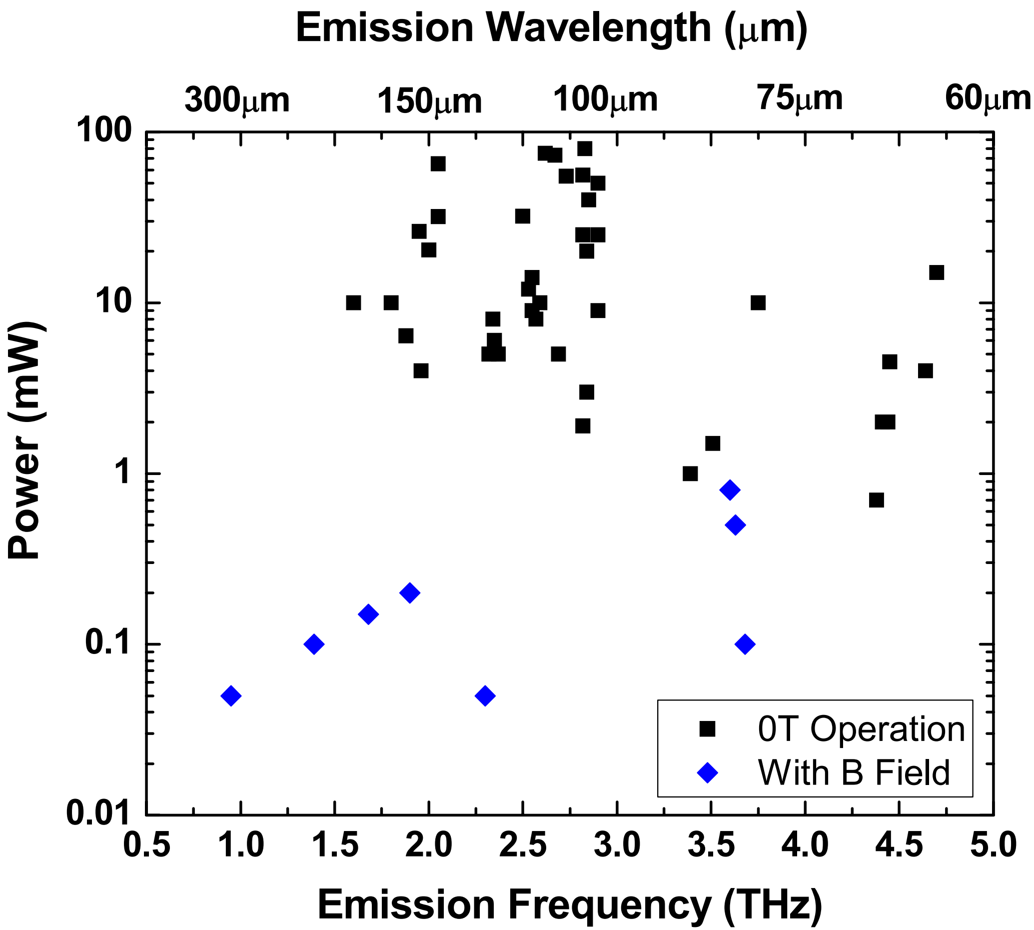
Transfer of QCLs between growth systems

- **Successful transfer of multiple AR designs**
- **Similar performance levels (P, T, J_{th})**
- **Different frequency observed for same AR thickness**
  - *- under investigation*

Frequency Span



- Over 60 working QCLs, incorporating in excess 30 different ARs
- Since 2002 frequency spans 0.95THz – 4.8THz (300μm – 62μm)

Summary

- Highlighted issues associated with growth
- Study of Active Region robustness presented
- Minor tweaks to Active Region
- Transfer of structures between growth reactors
- Span of frequencies so far