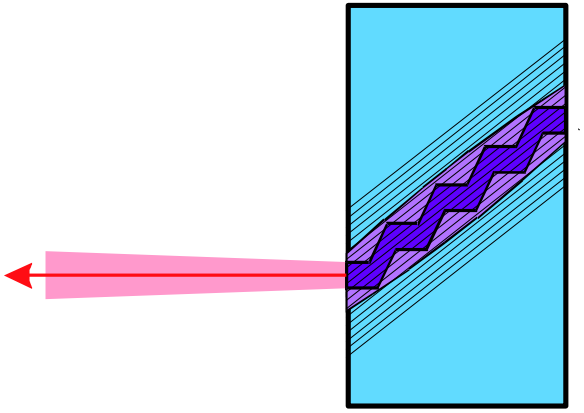
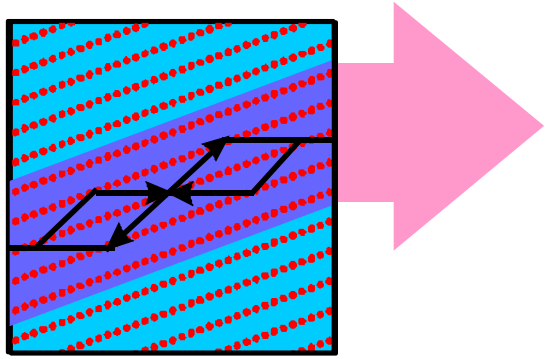
a-DFB & PHOTONIC CRYSTAL DFB ANTIMONIDE MID-IR LASERS





3rd Workshop on the Fabrication, Characterization, & Applications of 6.1 Å III-V Semiconductors (Snowbird Utah, 1 August 2001)

W. W. Bewley, I. Vurgaftman, C. L. Felix, R. E. Bartolo, J. R. Lindle, & J. R. Meyer, *Naval Research Laboratory*

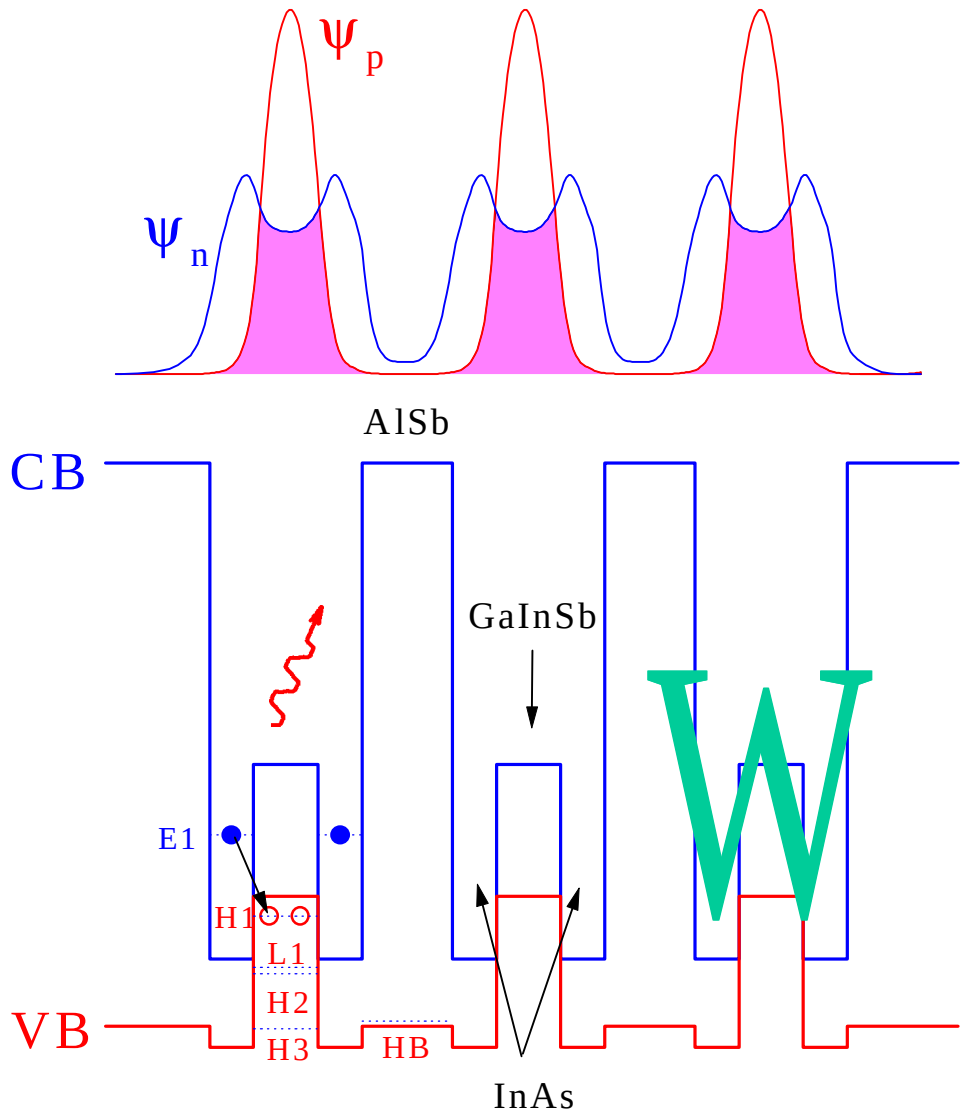
G. W. Turner, M. J. Manfra, A. Goyal, & A. Sanchez, *MIT Lincoln Laboratory*

H. Lee & R. U. Martinelli, *Sarnoff Corp.*

OVERVIEW

- Brief review of the Type-II "W" Antimonide laser – Concept & configurations
- Critical beam-quality issue – *How can we maintain low output divergence for a broad (high-power) pump stripe?*
- Mid-IR angled-grating distributed feedback (α-DFB) laser
- α-DFB with *Virtual Mesa* or *Spoiler geometry* – Produced by ion bombardment
- Photonic crystal distributed feedback (PCDFB) laser – Theoretical projections + Demo

TYPE-II "W" LASER



Meyer et al. APL 67, 757 (1995)

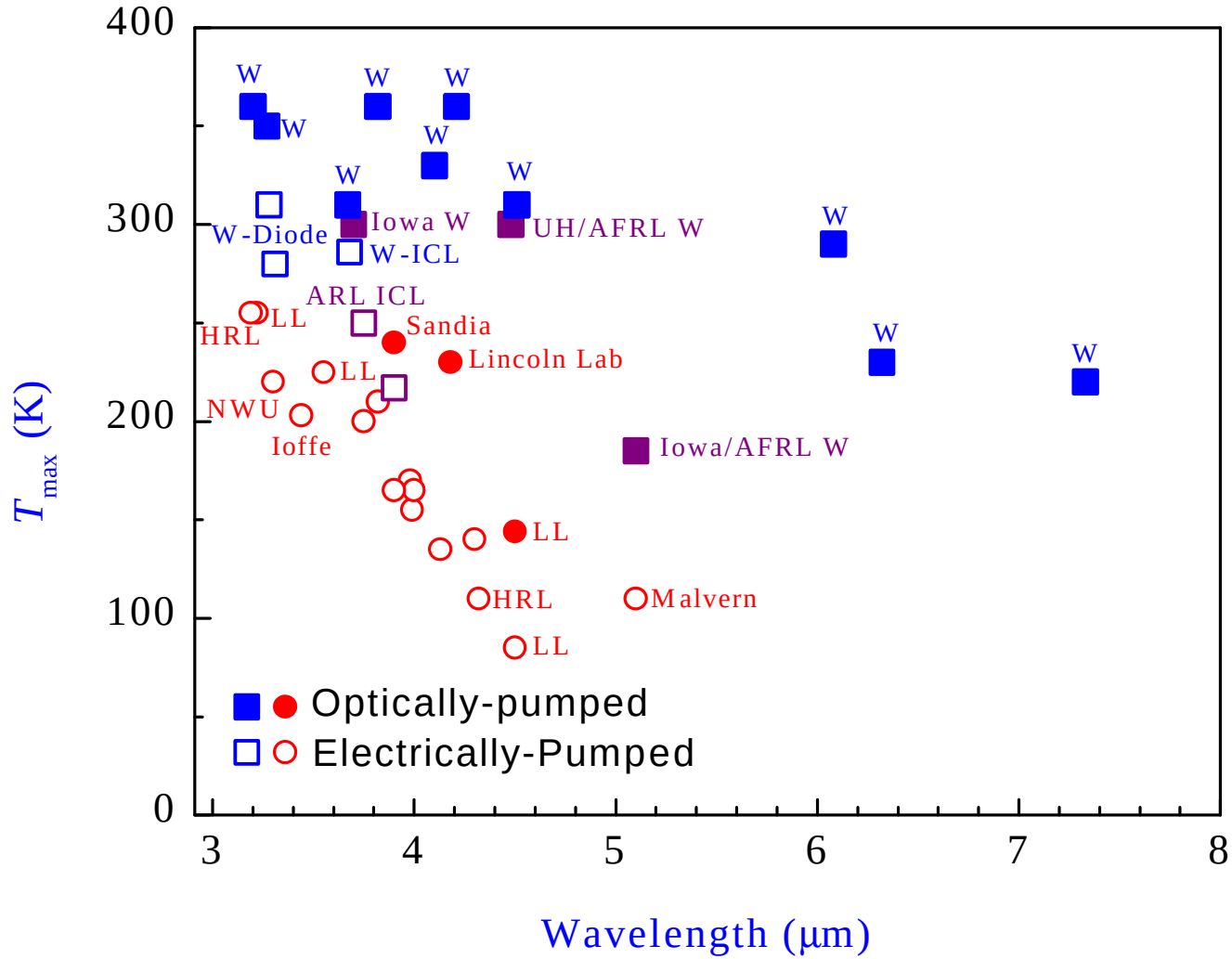
ADVANTAGES:

- (1) Strong wavefunction overlap
  - For high gain
- (2) 2D DOS for both electrons & holes
  - For high differential gain
- (3) Excellent electrical confinement
  - Prevents leakage
- (4) Auger suppression *(5-10 confirmed in lasers)*
  - Reduces threshold at high *T*

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

INTERBAND III-V MID-IR LASERS (Pulsed)

Stokes et al., JAP 86, 4729 (1999)



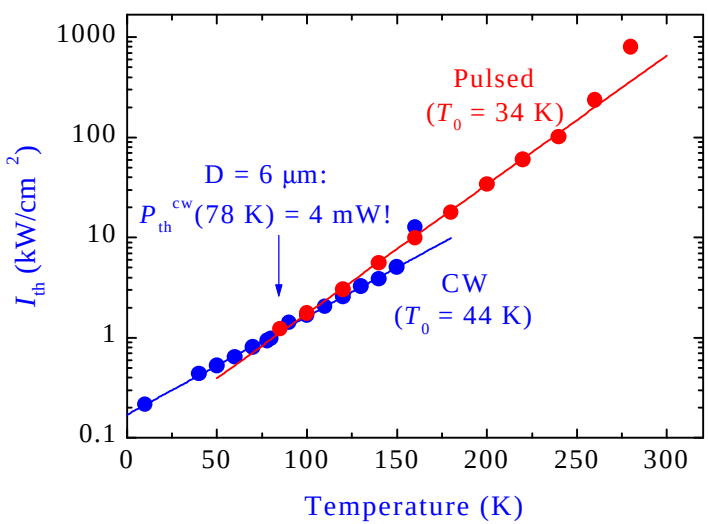
W still only room-temperature interband III-V laser beyond 3 μm – Also longest λ

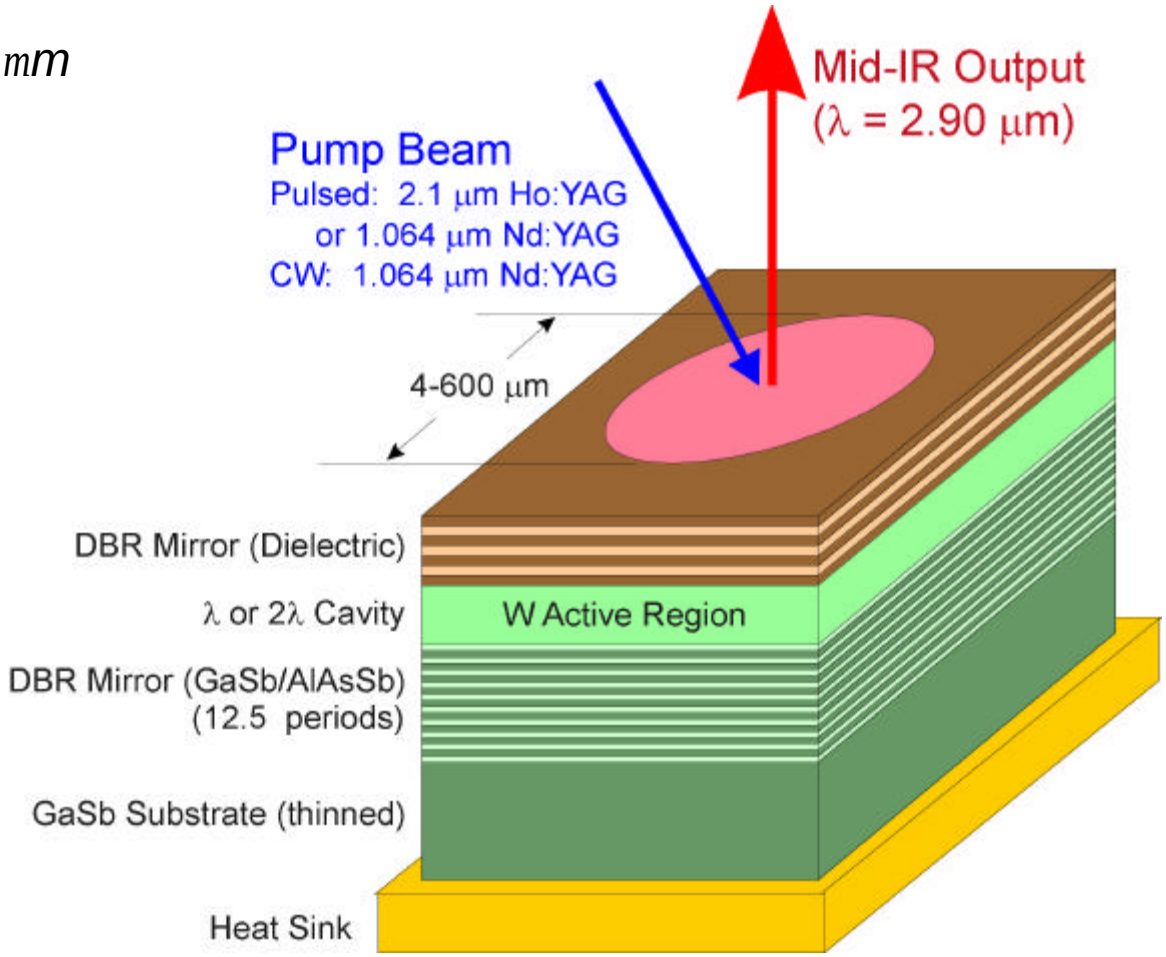
W MID-IR VCSEL *[with Dave Chow et al., HRL]*

First III-V VCSEL beyond 2.2 mm

Motivations:

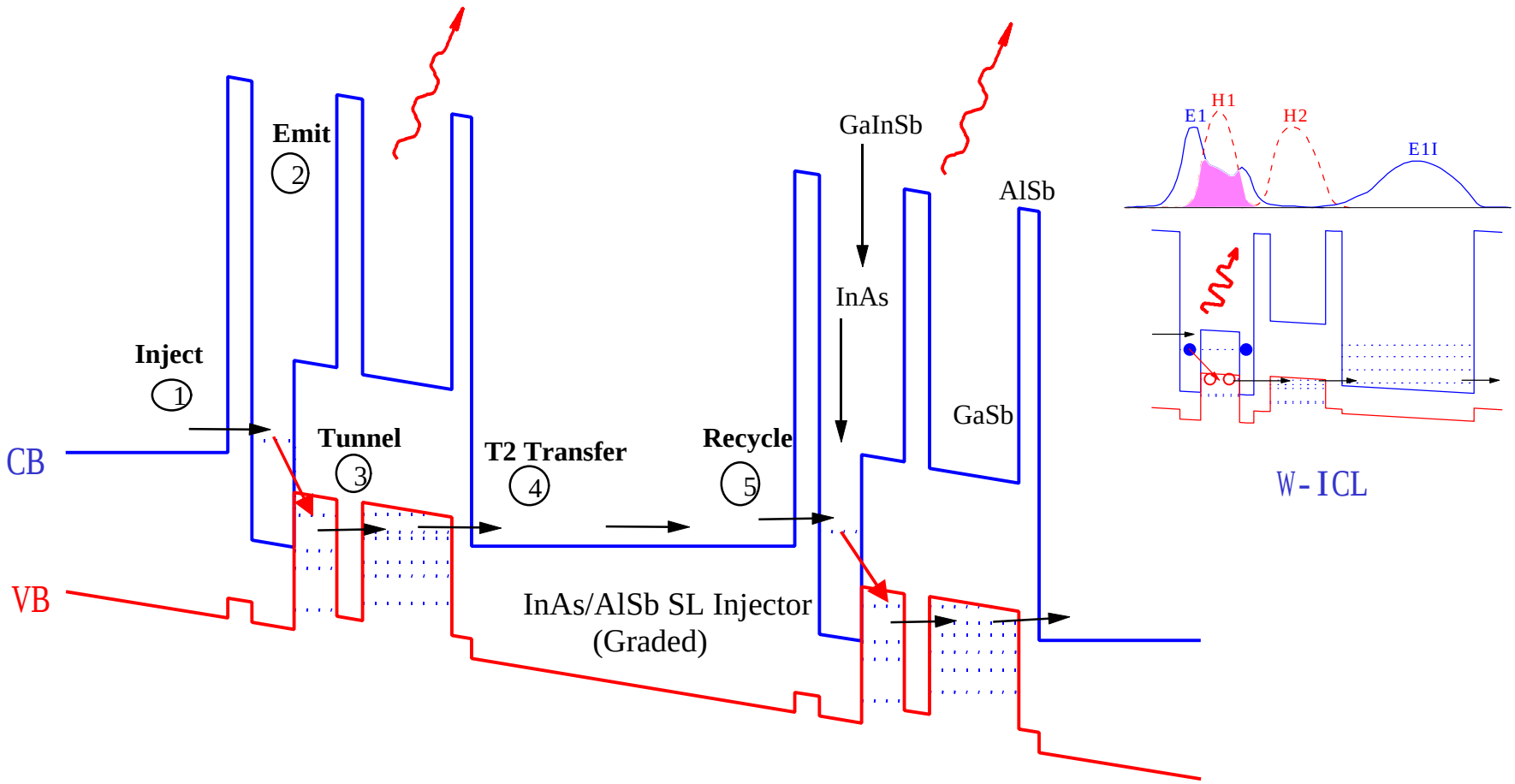
- *Circular beam*
- *Single-mode output*
- *Ultra-low threshold*
- *2D arrays*





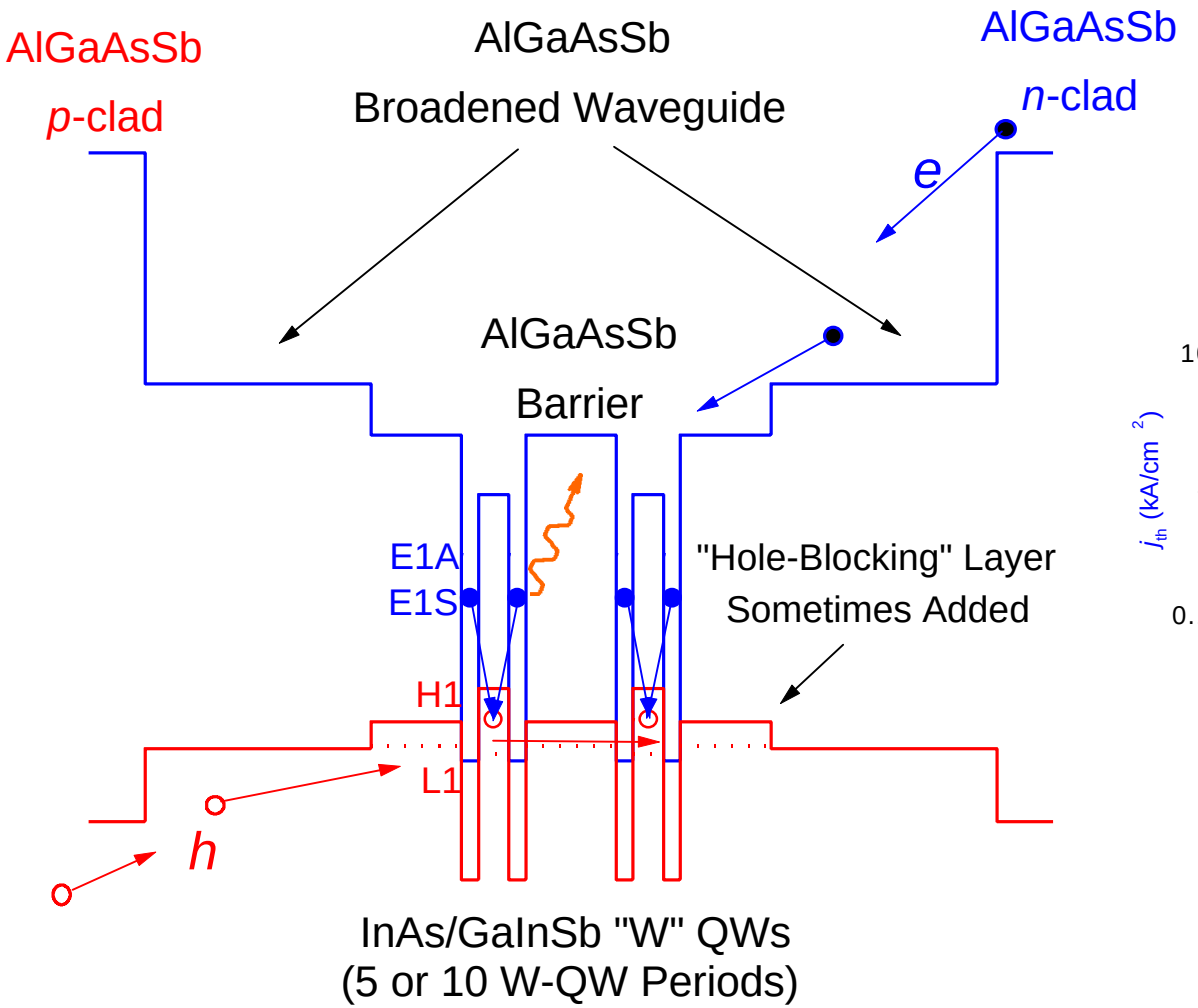
Felix et al., APL 71, 3483 (1997); Bewley et al., PTL 10, 660 (1998)

W INTERBAND CASCADE LASER [with U. Houston]



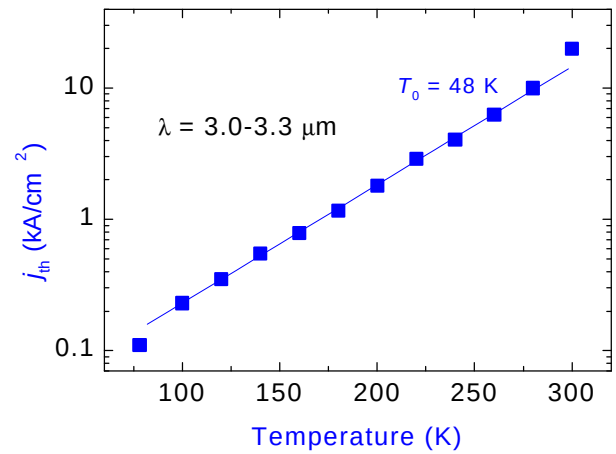
Pulsed W-ICL operated to 286 K *[Olafsen et al., APL 72, 2370 (1998)]*

W DIODES *[with Sarnoff Corp.]*



Pulsed T_{max} = 310 K

[Lee et al., EL 35, 1743 (1999)]



CW T_{max} = 200 K

[Bewley et al., APL 76, 256 (2000)]

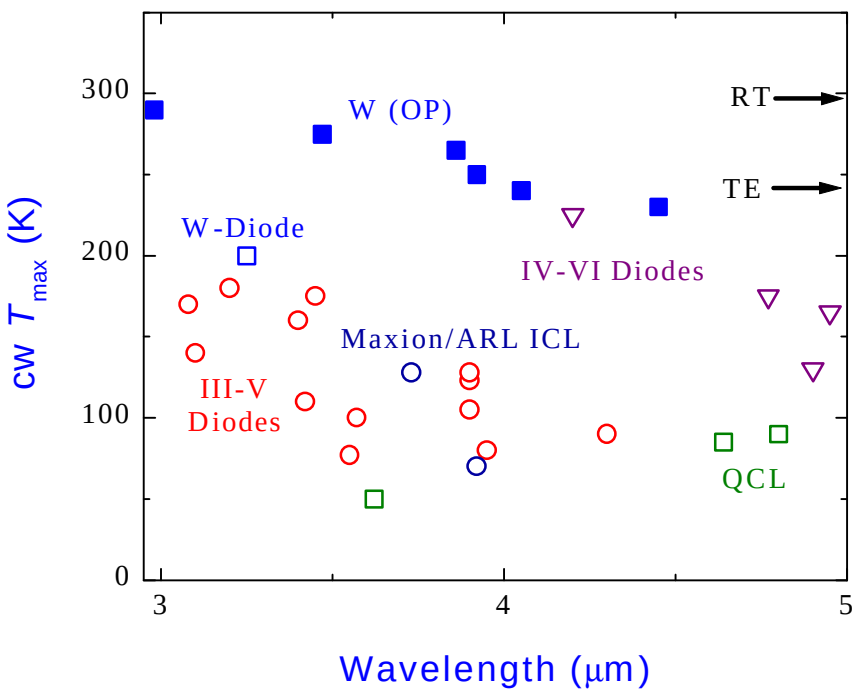
Predict room-temperature cw with 1-2 QWs

Interperiod hole transport via L1 states

CW PERFORMANCE

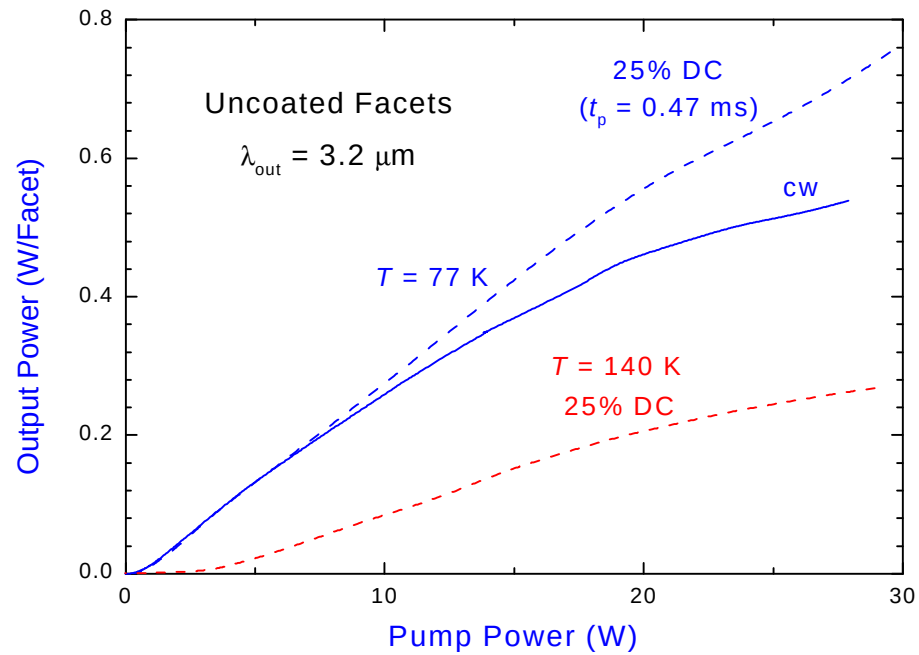
CW T_{max} (All 3-5 μm Semiconductor Lasers)

[Bewley et al., APL 74, 1075 (1999)]



CW Power

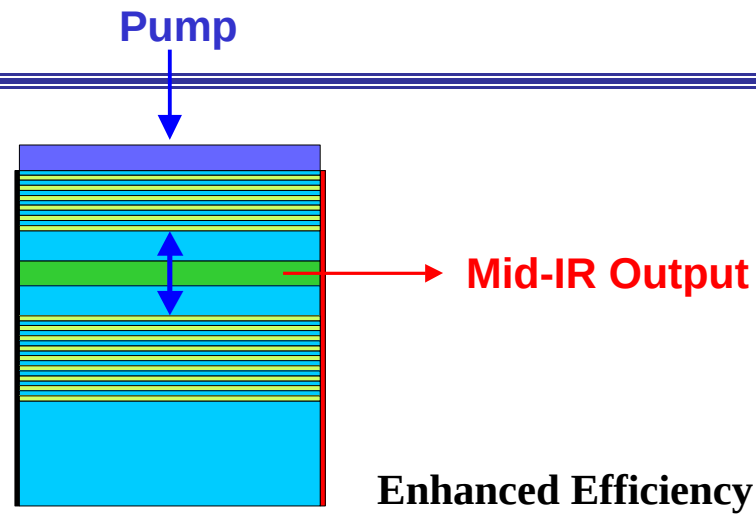
[Bewley et al., JQE 35, 1597 (1999)]



To further increase cw output power, need to improve efficiency: (1) IA, (2) OPIC

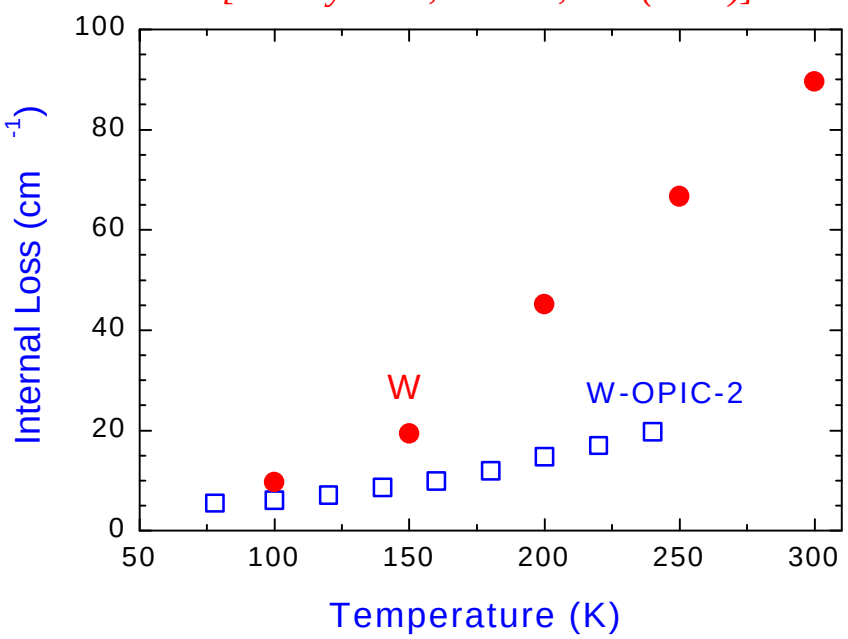
OPTICAL PUMPING INJECTION CAVITY (OPIC)

***OPIC*: Fabry-Perot etalon for pump beam – Strong absorptance with only a few QWs!**



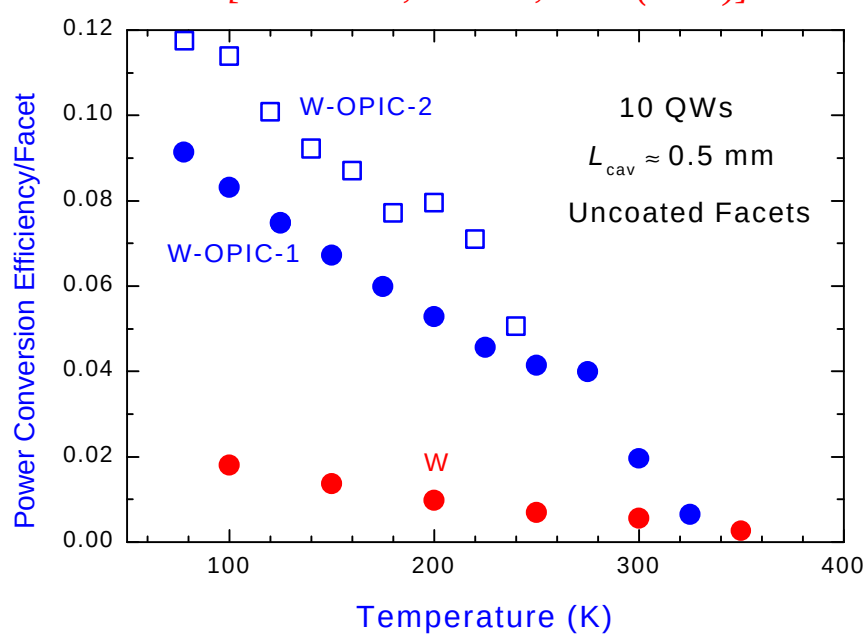
Reduced Loss

[Bewley et al., PTL 12, 477 (2000)]



Enhanced Efficiency (Pulsed)

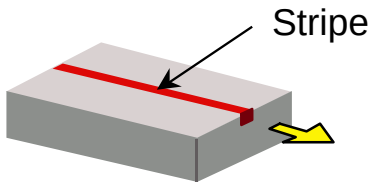
[Felix et al., APL 75, 2876 (1999)]



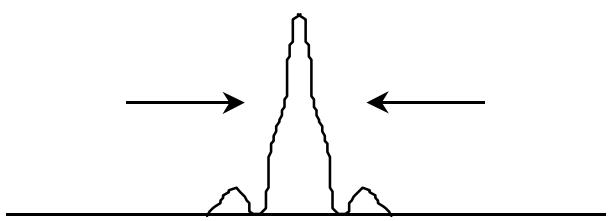
Preliminary quasi-cw: P_{out} = 1.3 W at 25% duty cycle, 2 W at 10% duty cycle

BEAM QUALITY vs. STRIPE WIDTH

Narrow stripe (< a few λ):

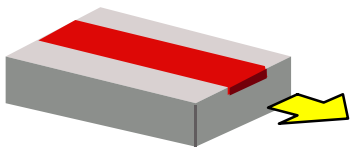


Single lateral mode

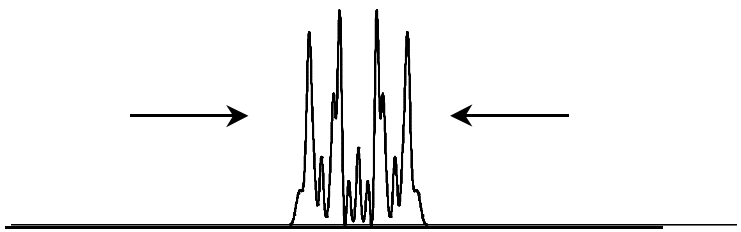


Near-diffraction-limited

Wide stripe (>> λ) for high power:



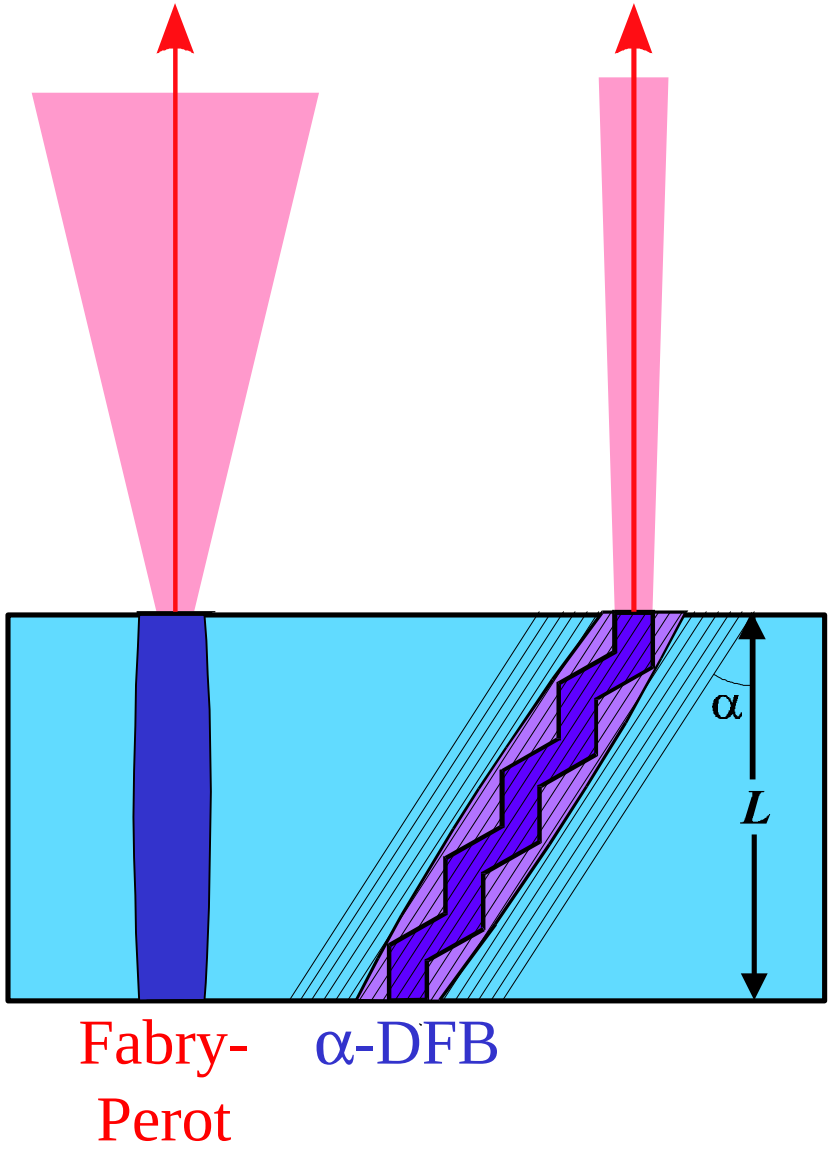
Many lateral modes



Wide angular divergence

Challenge: Good beam quality from a wide stripe?

ANGLED-GRATING DISTRIBUTED FEEDBACK LASER (α-DFB)



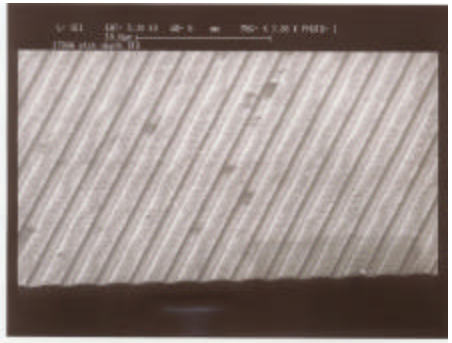
- Originally developed by SDL for visible/near-IR (λ = 0.6-1.55 μm)
- NRL demonstrated first mid-IR α-DFBs (optically-pumped)

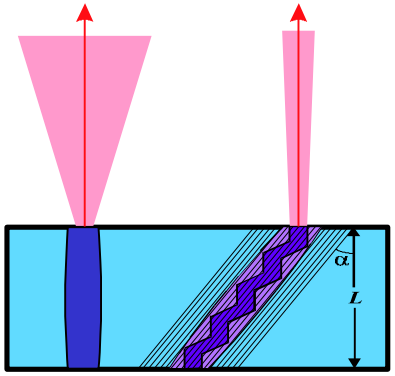
Bartolo et al., APL 76, 3164 (2000)

Zigzag path of diffracted beam yields high degree of angular selectivity

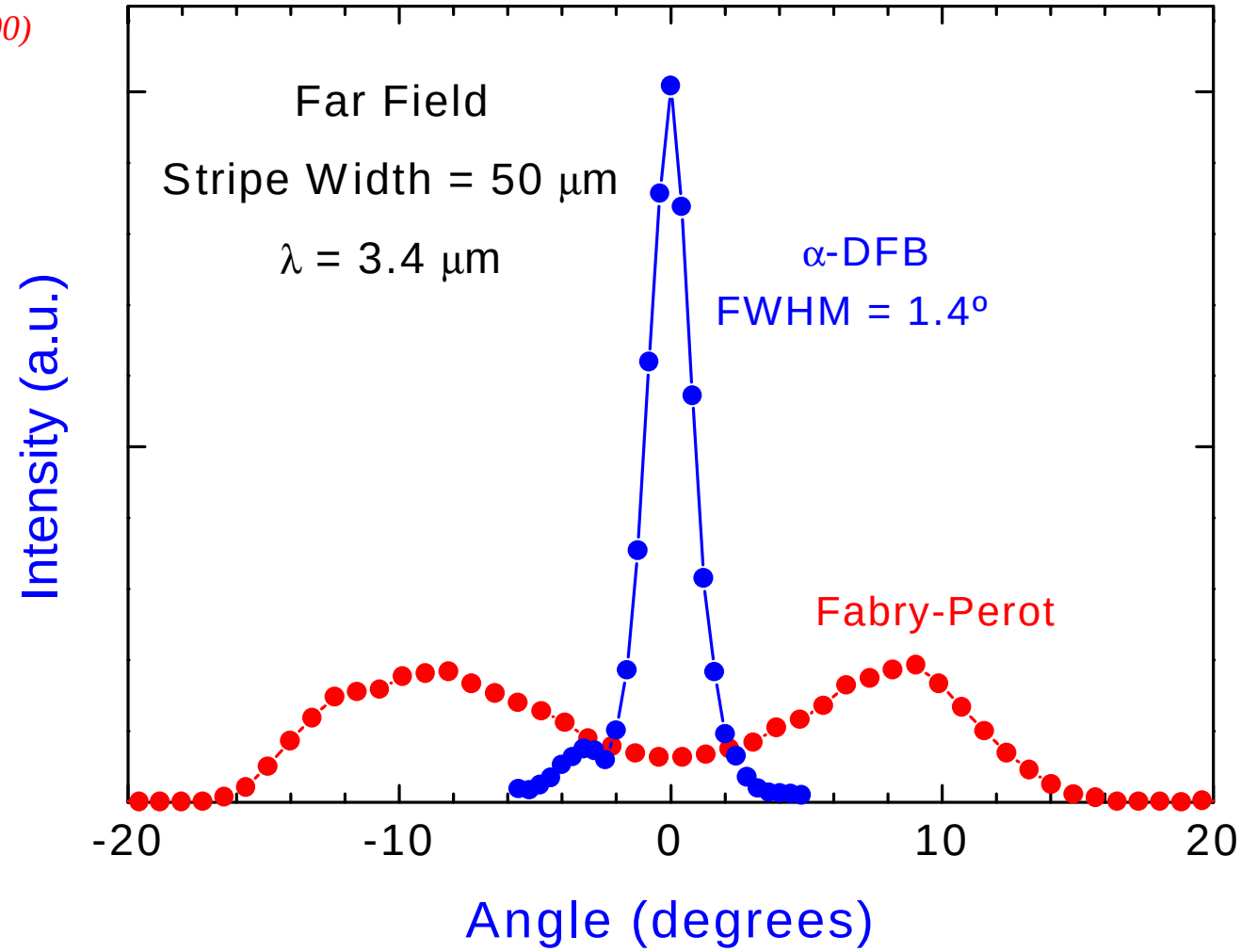
MID-IR α-DFB – FAR FIELD

Bartolo et al., APL 76, 3164 (2000)





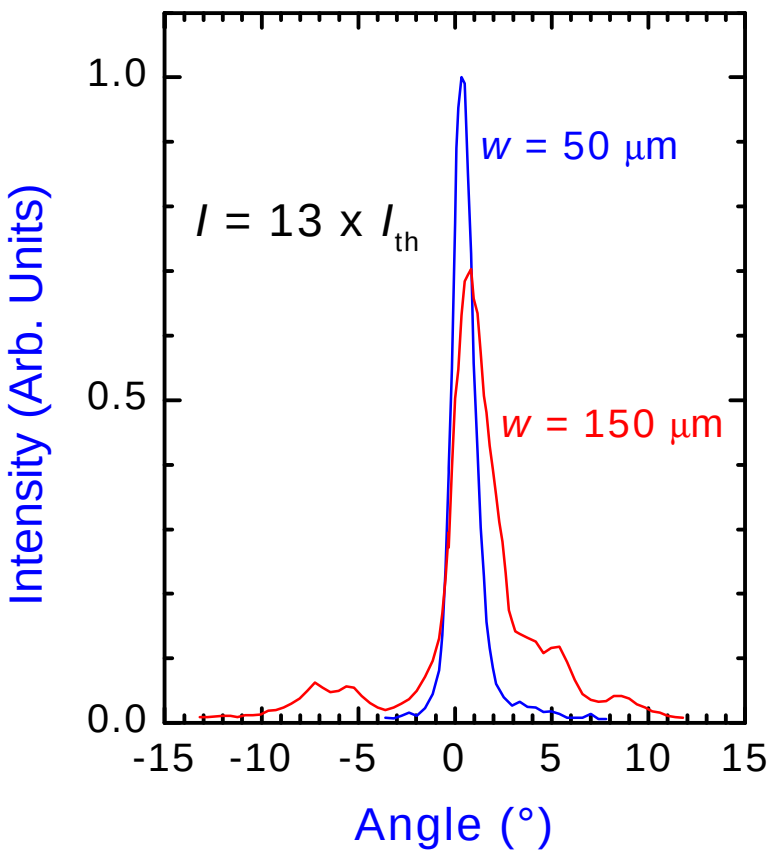
F-P α-DFB

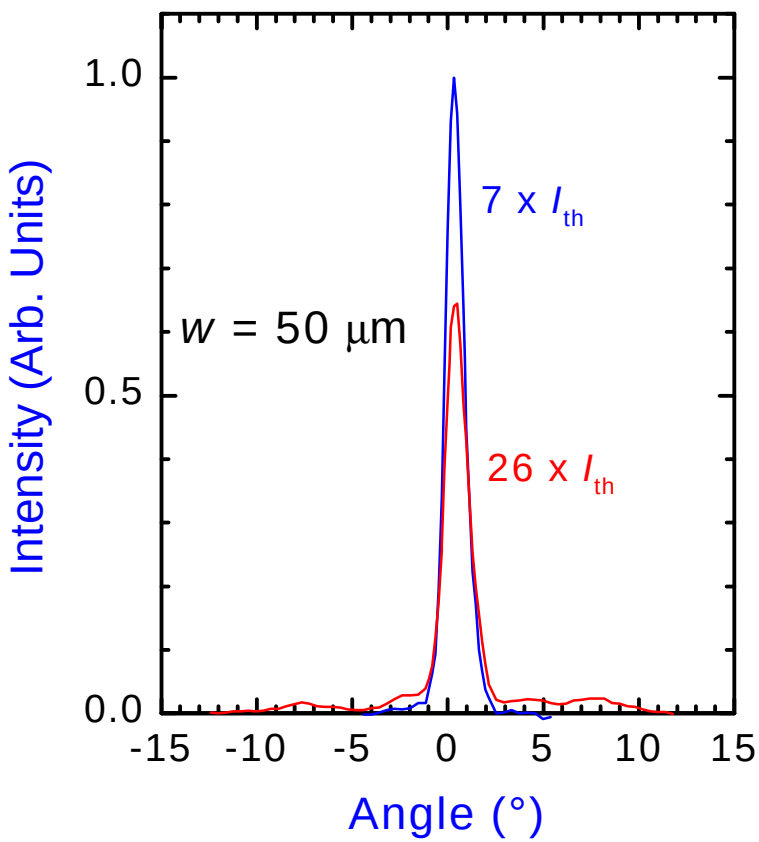


Near-diffraction-limited – ***But only to stripe widths £ 50 mm***

FAR FIELD vs. STRIPE WIDTH, PUMP INTENSITY

Mid-IR α-DFB beam quality degrades with both increasing pump stripe width & increasing pump intensity

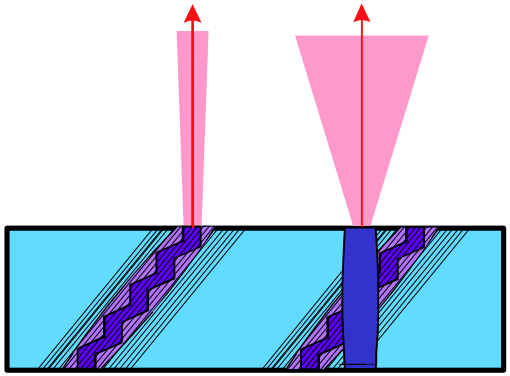




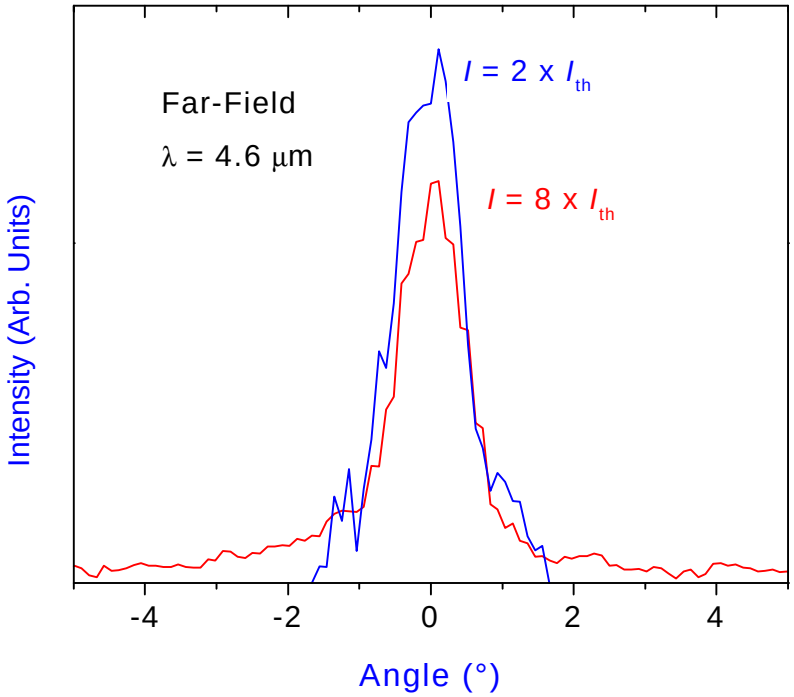
FAR FIELD + NEAR FIELD

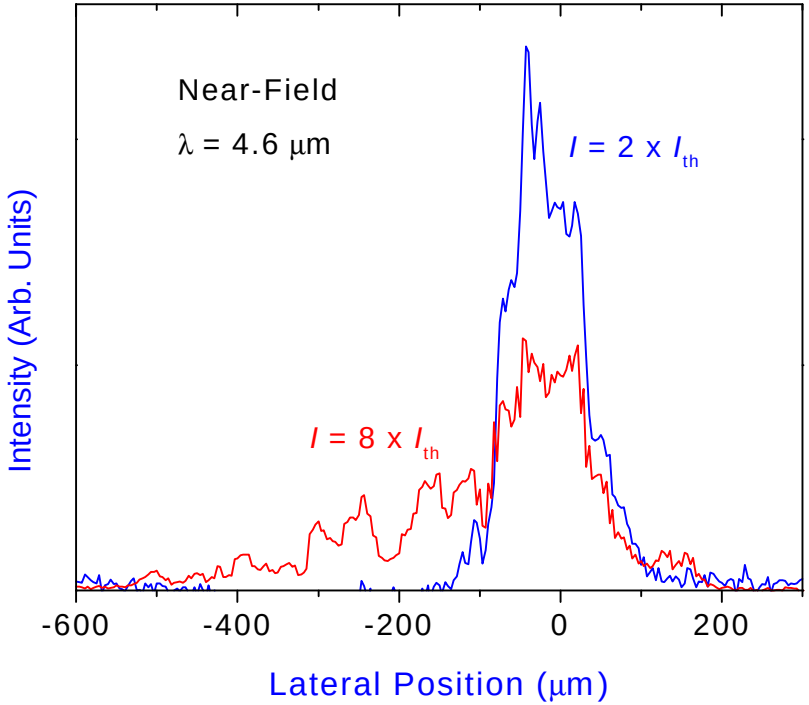
Data suggest beam-quality degradation at wide pump stripes & high pump intensities due to Fabry-Perot-like facet-to-facet lasing – Theory agrees

Also confirmed by quasi-cw near-field characterization (Anish Goyal, MIT-LL):

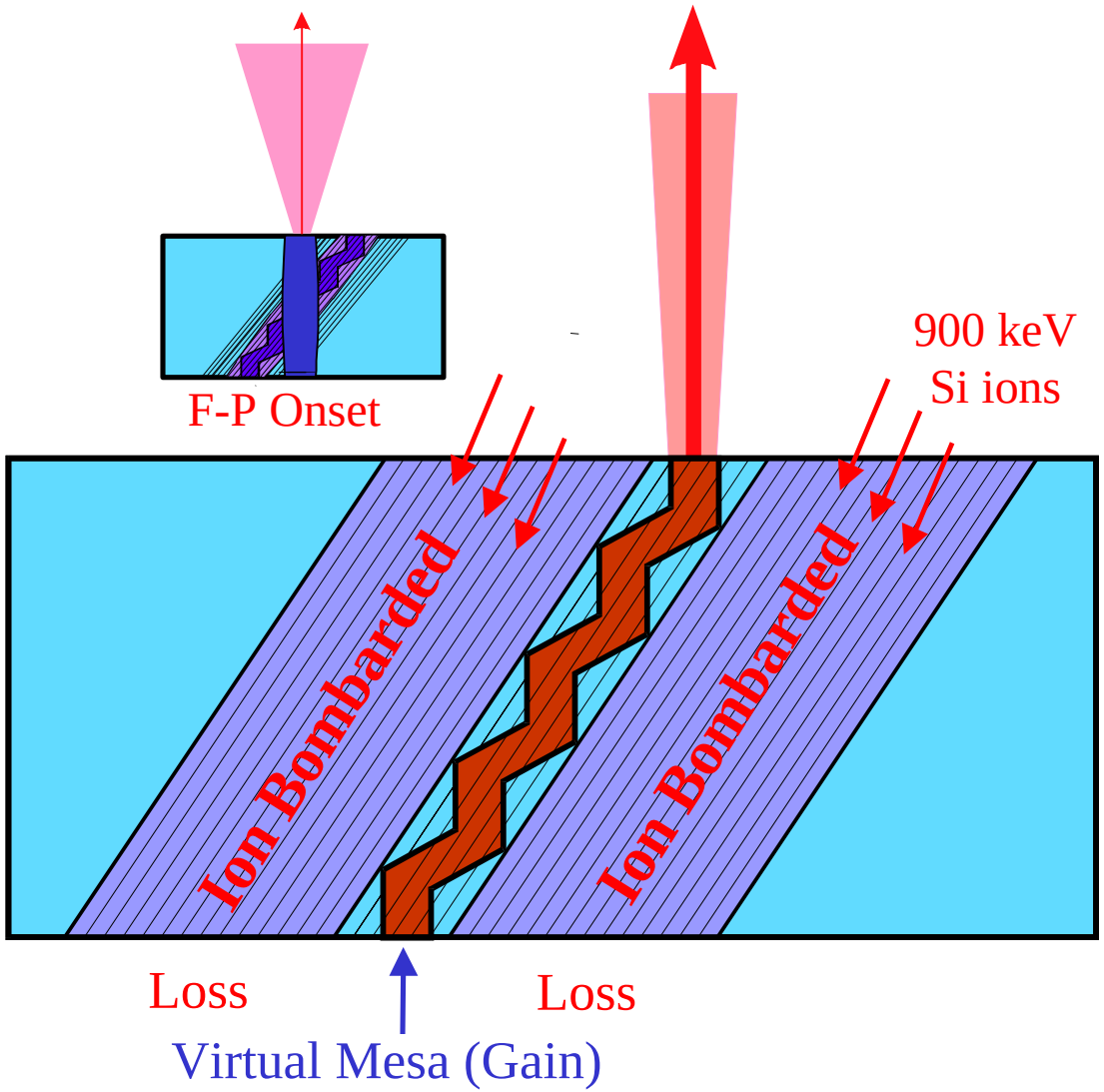


F-P Onset



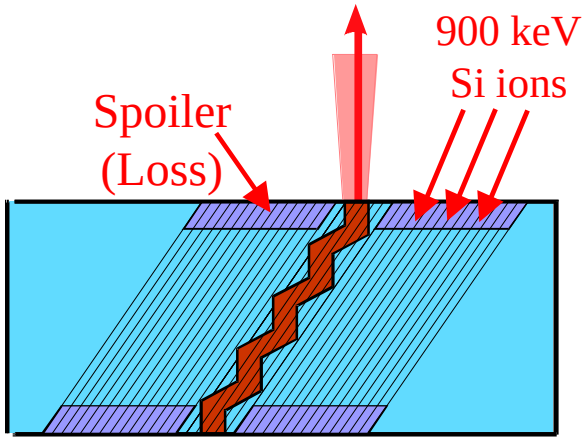


MODE CONFINEMENT WITH ION-BOMBARDMENT

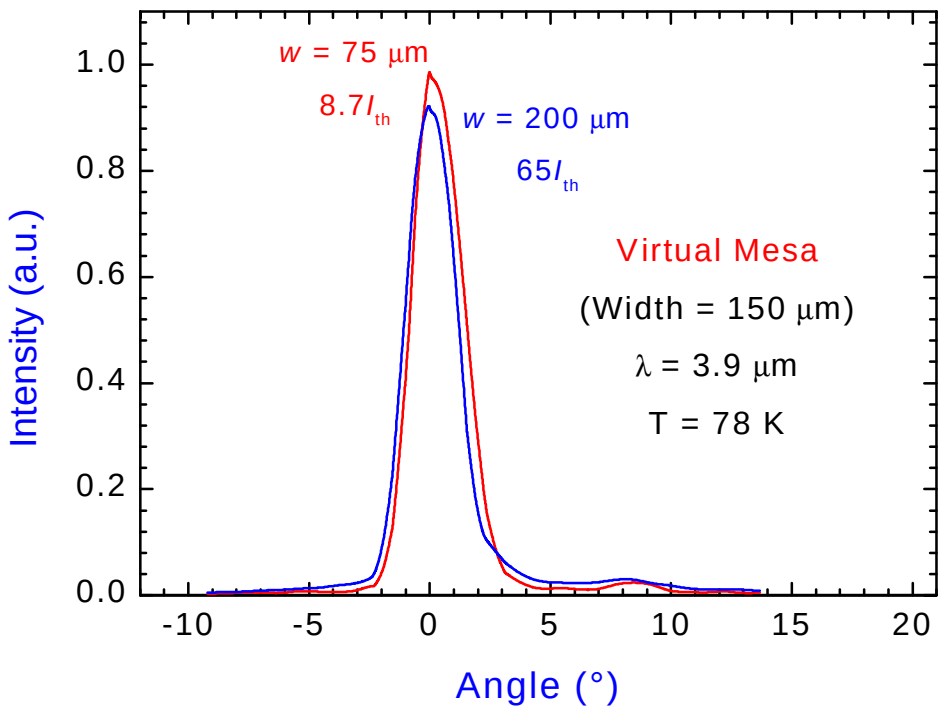


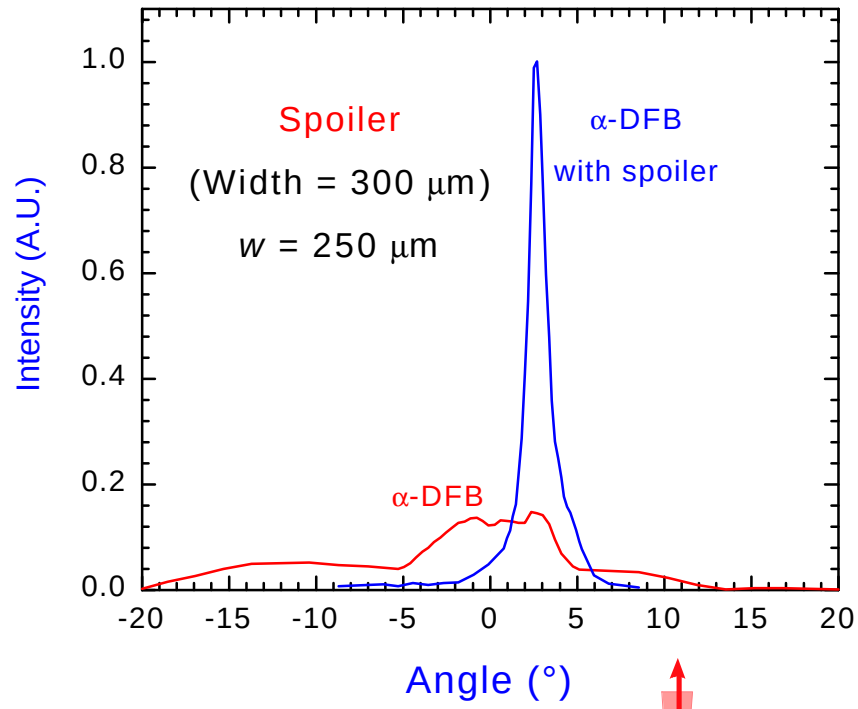
- Bombardment damage turns gain into loss
- Suppresses Fabry-Perot modes
- Alternative: Ion-bombarded "spoilers":

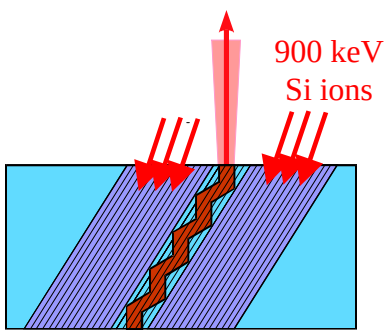
Bartolo et al., APL 78, 3394 (2001)



VIRTUAL MESA & SPOILER a-DFBs

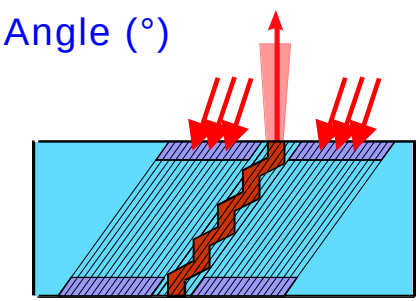






Virtual Mesa

Samples from George Turner (MIT-LL)

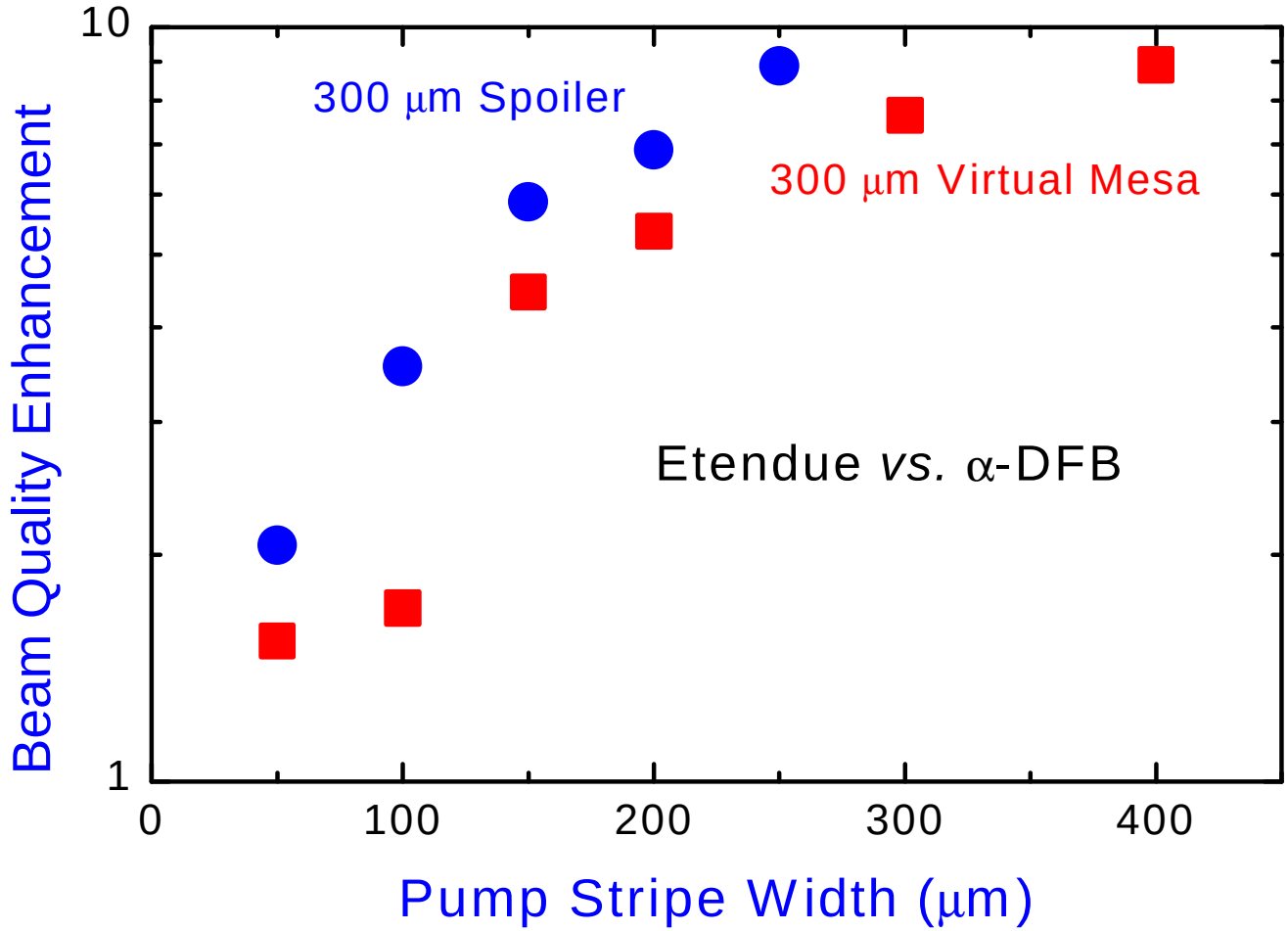


Spoiler

Virtual Mesa & Spoiler significantly improve beam quality at wide pump stripes – Fabry-Perot-like modes suppressed

BEAM QUALITY ENHANCEMENT

Combining angular divergence and spatial near-field contributions:

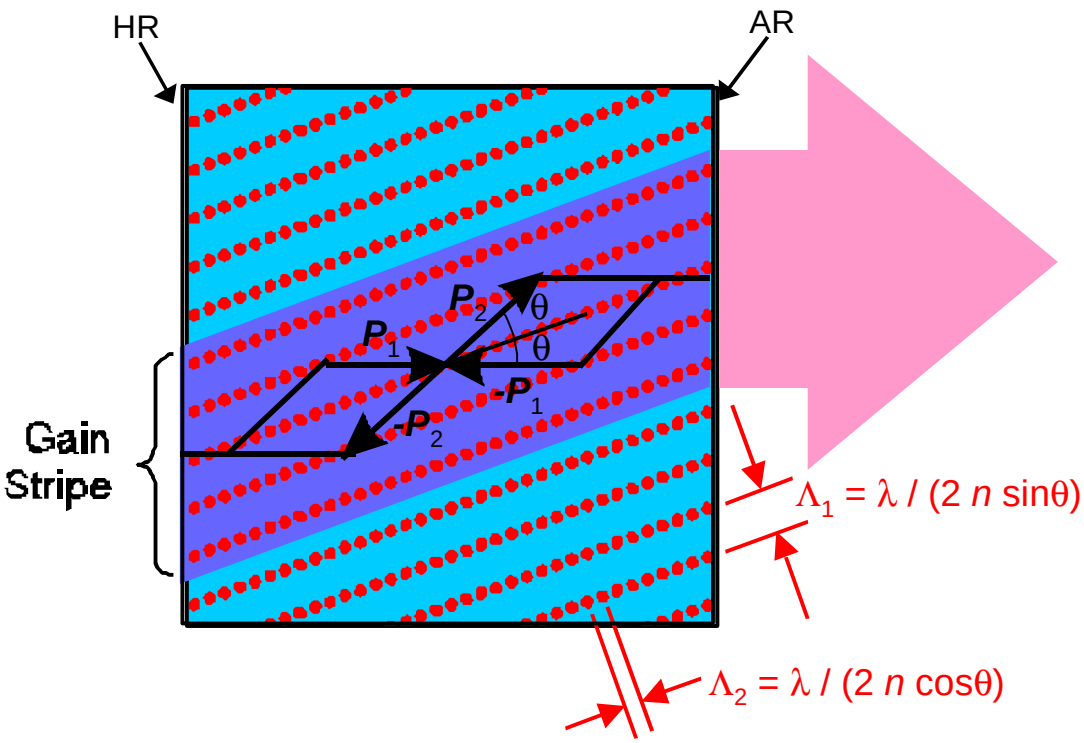


Etendue reduced by nearly order of magnitude! – However, some efficiency penalty so far

PHOTONIC CRYSTAL DFB LASER (PCDFB)

2D grating simultaneously diffracts along two axes (Rows + Columns) – Combines & enhances best features of DFB (Spectral purity) & α-DFB (Narrow divergence)

Vurgaftman et al., APL 78, 1466 (2001)
See also: S. Kalluri et al., ASLA, AWA6 (1999)



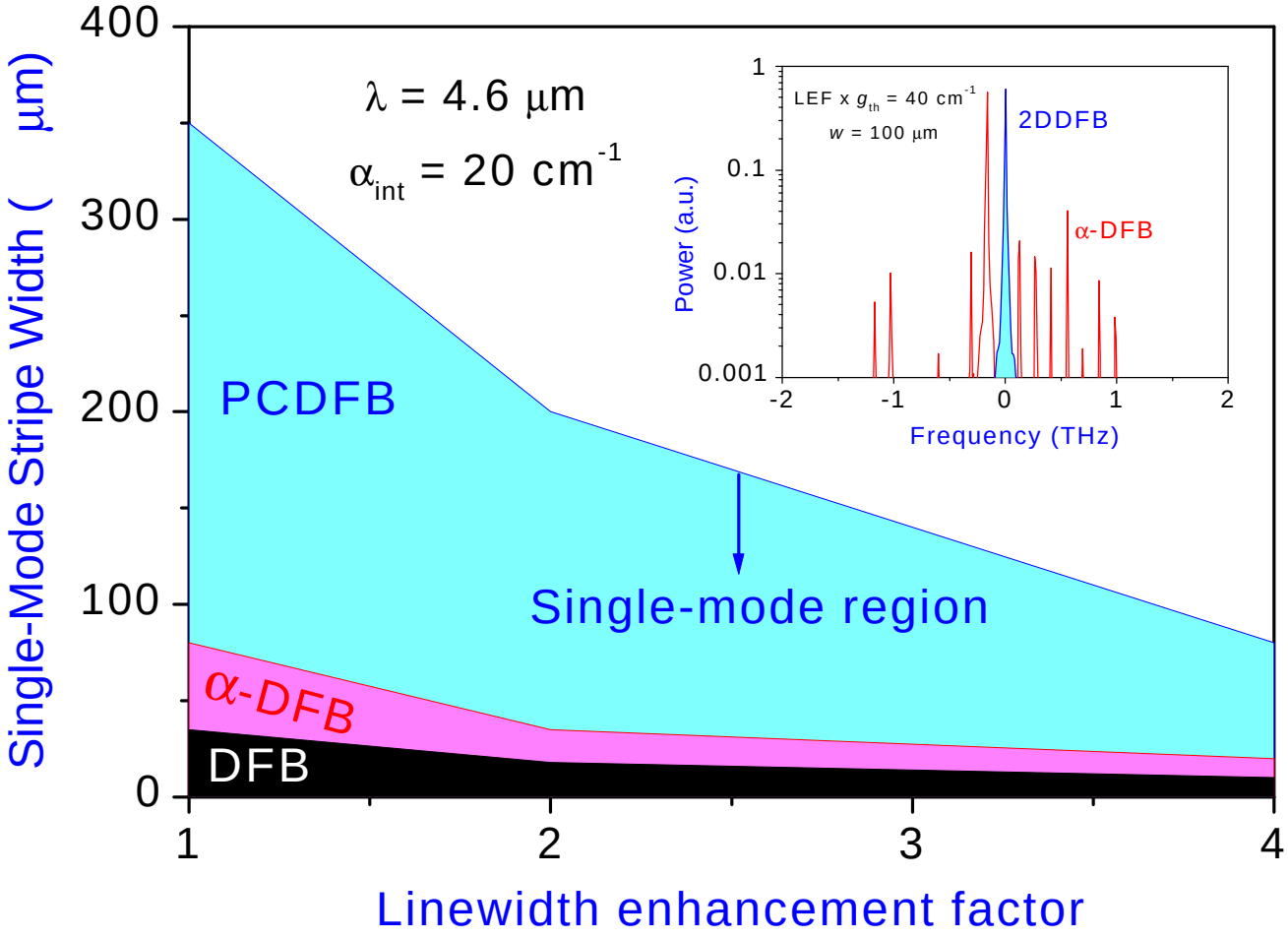
Both diffractions couple $\boldsymbol{P}_1$ to $\boldsymbol{P}_2$ + both counter-propagating waves ($-\boldsymbol{P}_1$ & $-\boldsymbol{P}_2$) – *Result is strong coherence across wide stripe (No filamentation)!*

Grating requires only shallow etch similar to conventional 1D DFB

Distinct from photonic bandgap lasers (with wide gap in all directions) – PCDFB has only narrow gap in selected directions

SINGLE-MODE PCDFBs

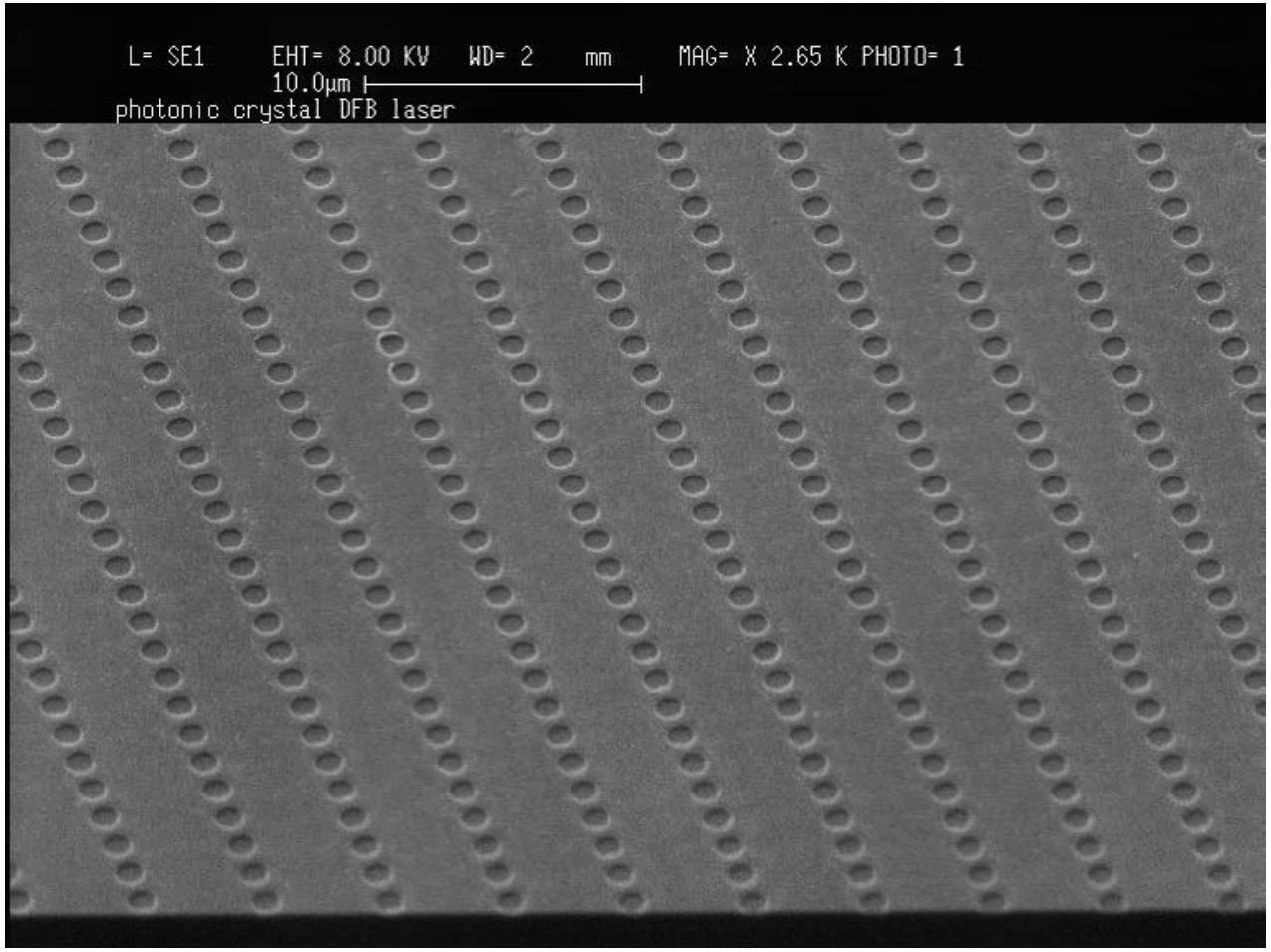
Novel Time-Domain Fourier Transform (TDFT) calculation developed to model performance *[Vurgaftman et al., APL 78, 1475 (2001)]* :



Project much higher single-mode power than any earlier approach

QUICK PCDFB LASER

Optimal 1st-order 2D grating requires e-beam lithography – *But 2nd-order grating features large enough to pattern with optical lithography*



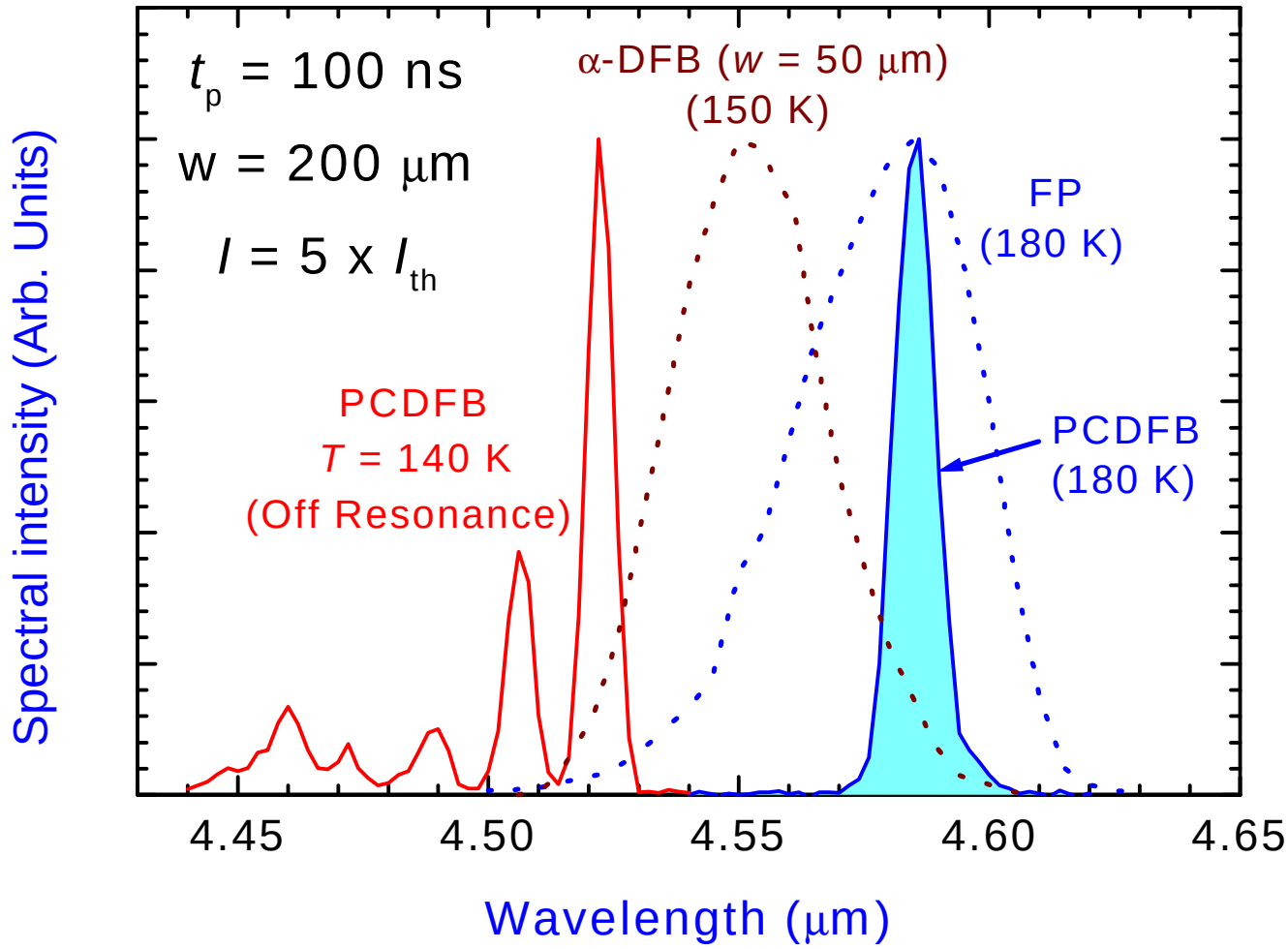
Patterned on Sarnoff Type-II "W" wafer grown for a-DFB (l » 4.6 mm)

Dimensions:
4.09 x 1.49 µm

Etch Depth: 100 nm

Tilt Angle: 20º

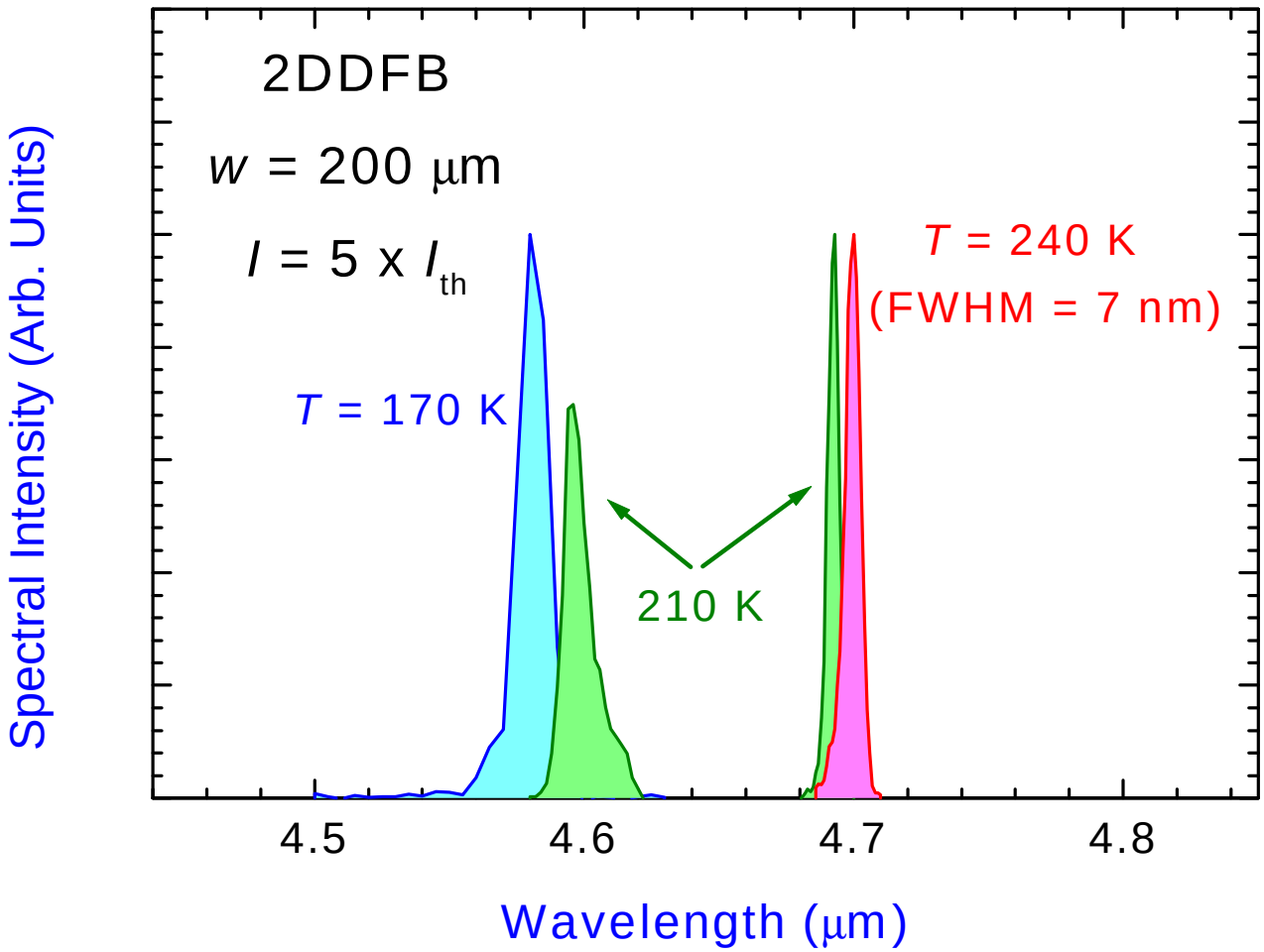
PCDFB SPECTRAL PROPERTIES



α-DFB from same wafer showed no appreciable spectral narrowing

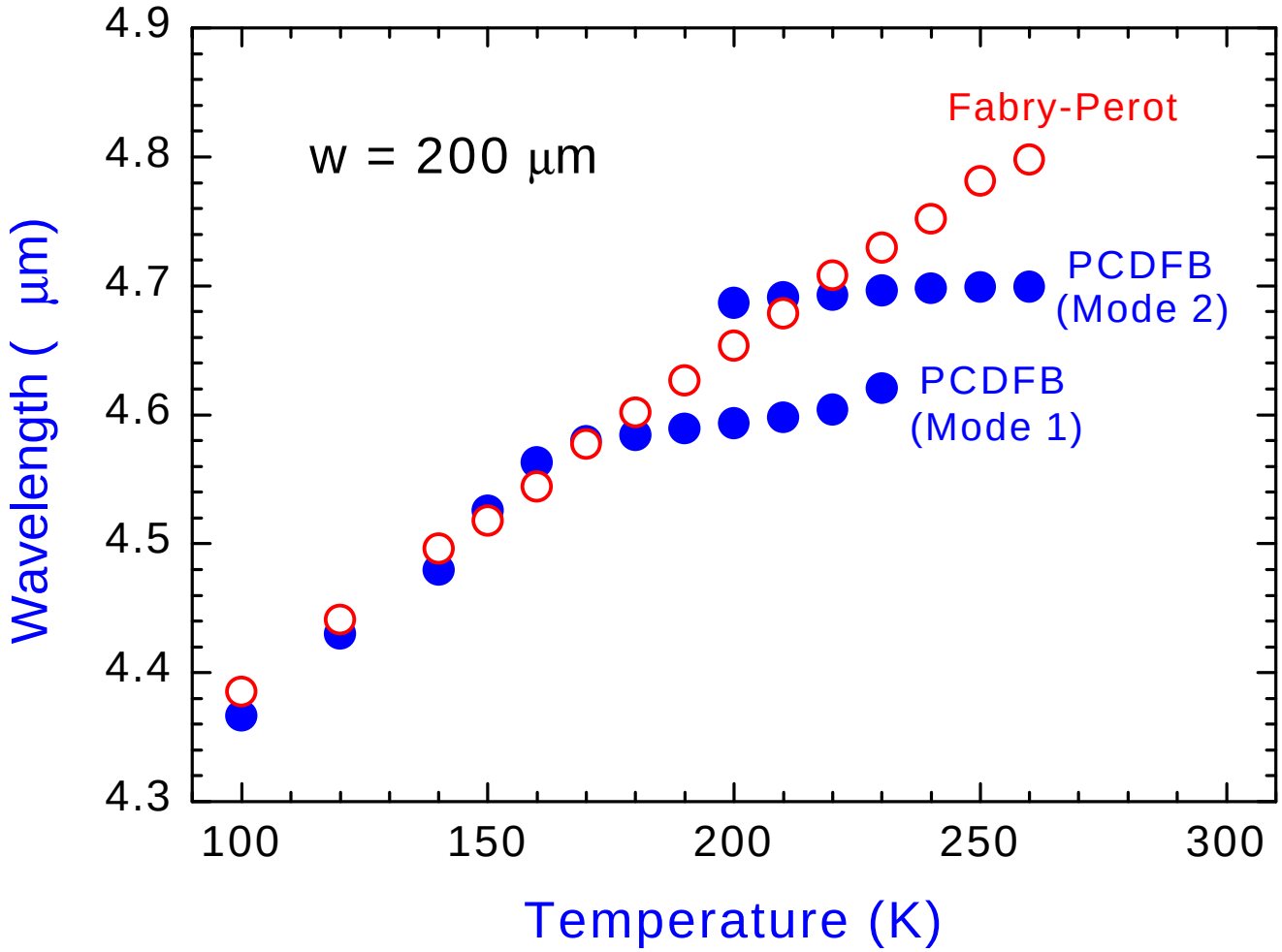
PCDFB line narrows by factor of 4 when on resonance (180 K)

2ND RESONANCE



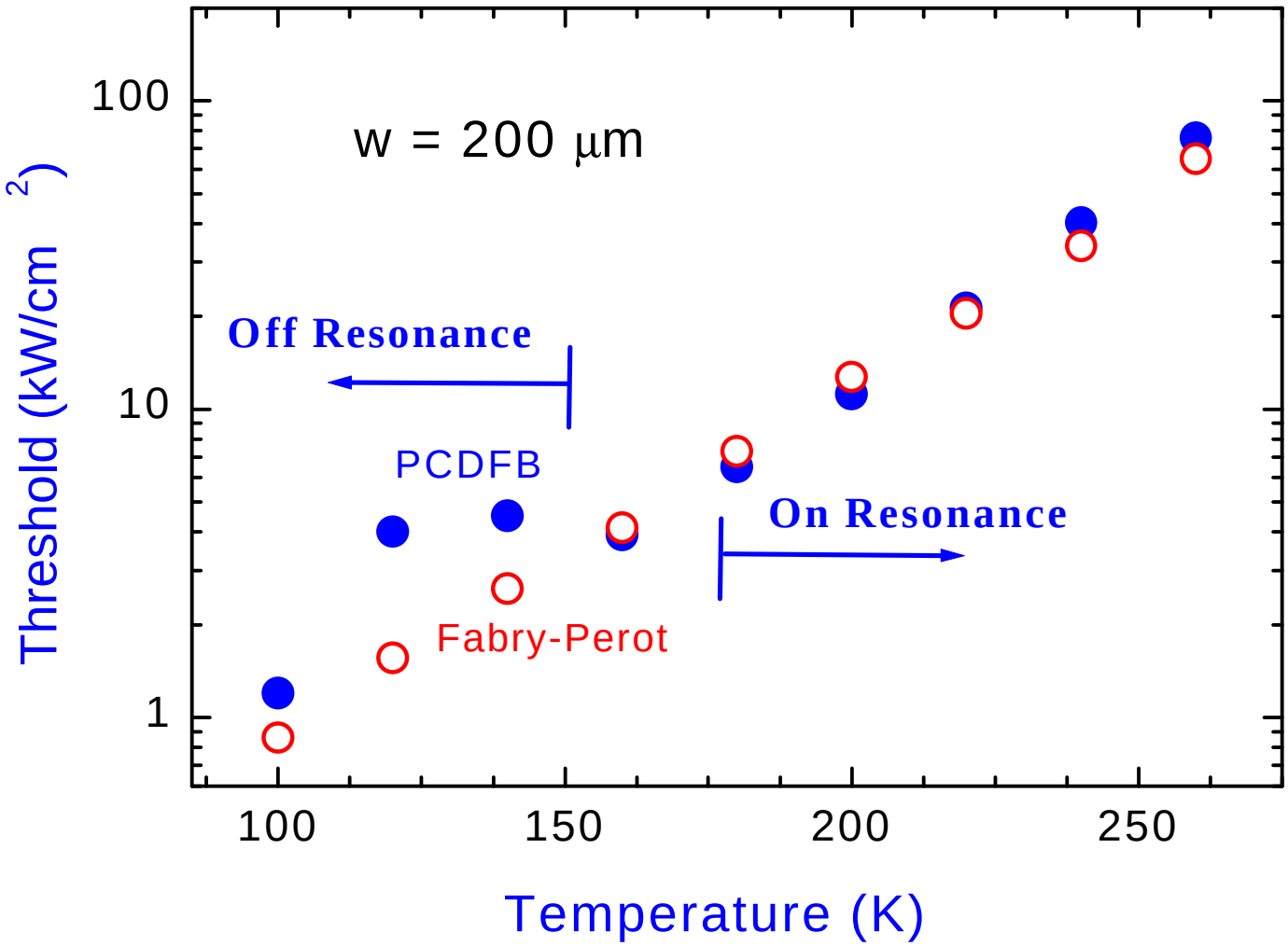
No output between the 2 resonances (4.6 μm & 4.7 μm), but *2-color laser* at intermediate *T* (*e.g.*, 210 K) – Order of magnitude narrowing at 240 K

WAVELENGTH vs. TEMPERATURE



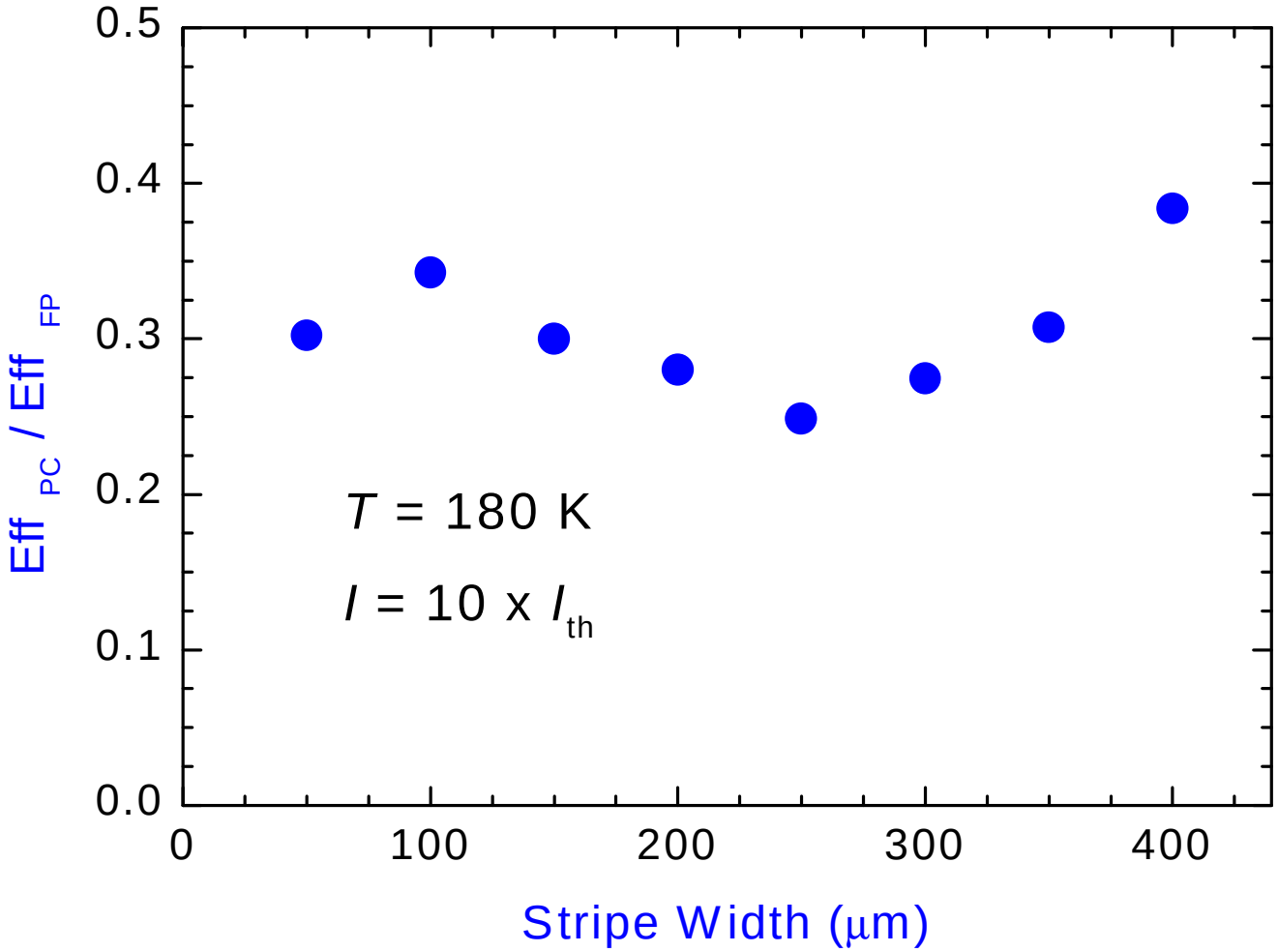
2 resonant PCDFB modes have nearly flat $\lambda(T)$

THRESHOLD vs. TEMPERATURE



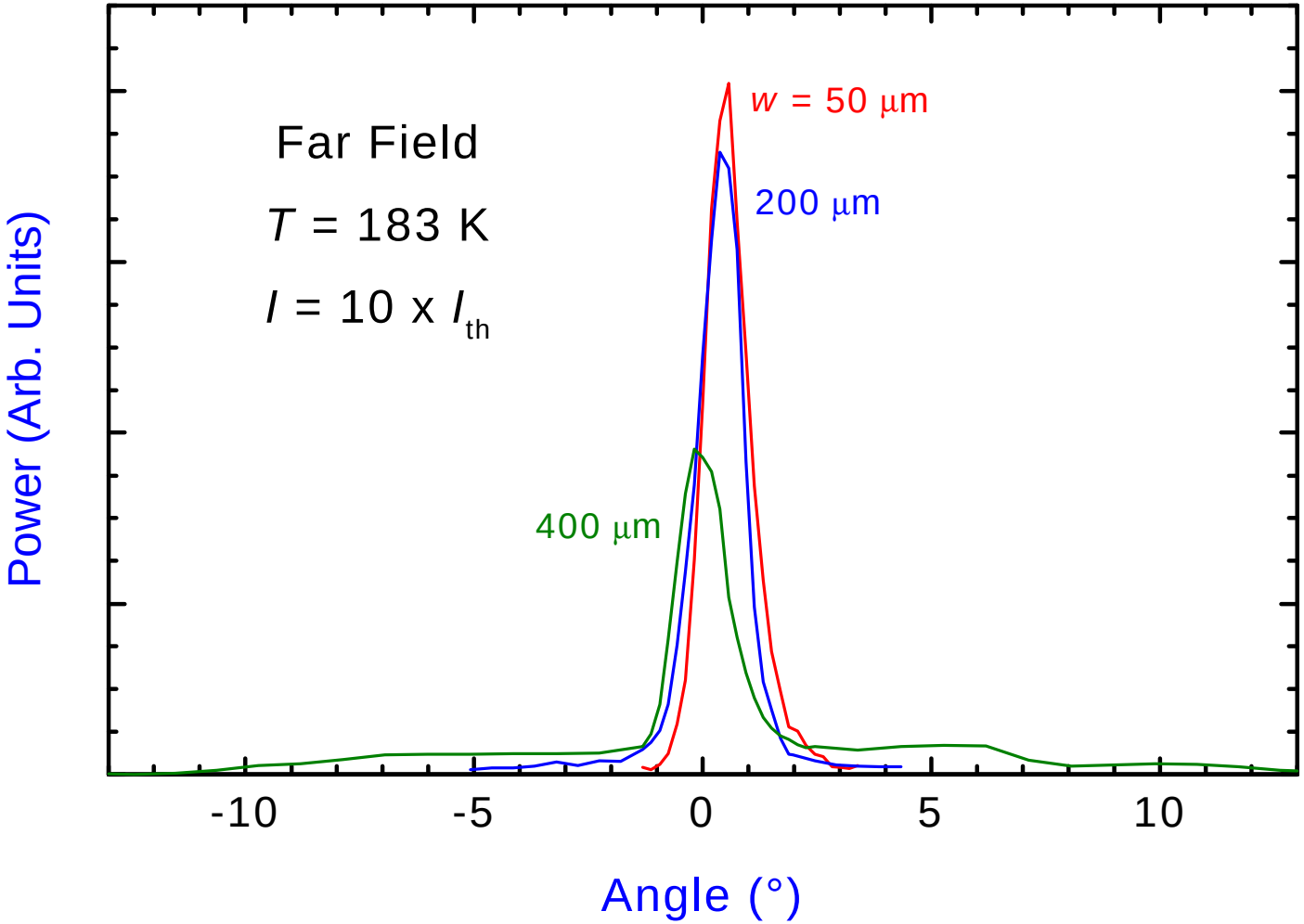
On-resonance PCDFB has same threshold as Fabry-Perot

PCDFB EFFICIENCY vs. STRIPE WIDTH



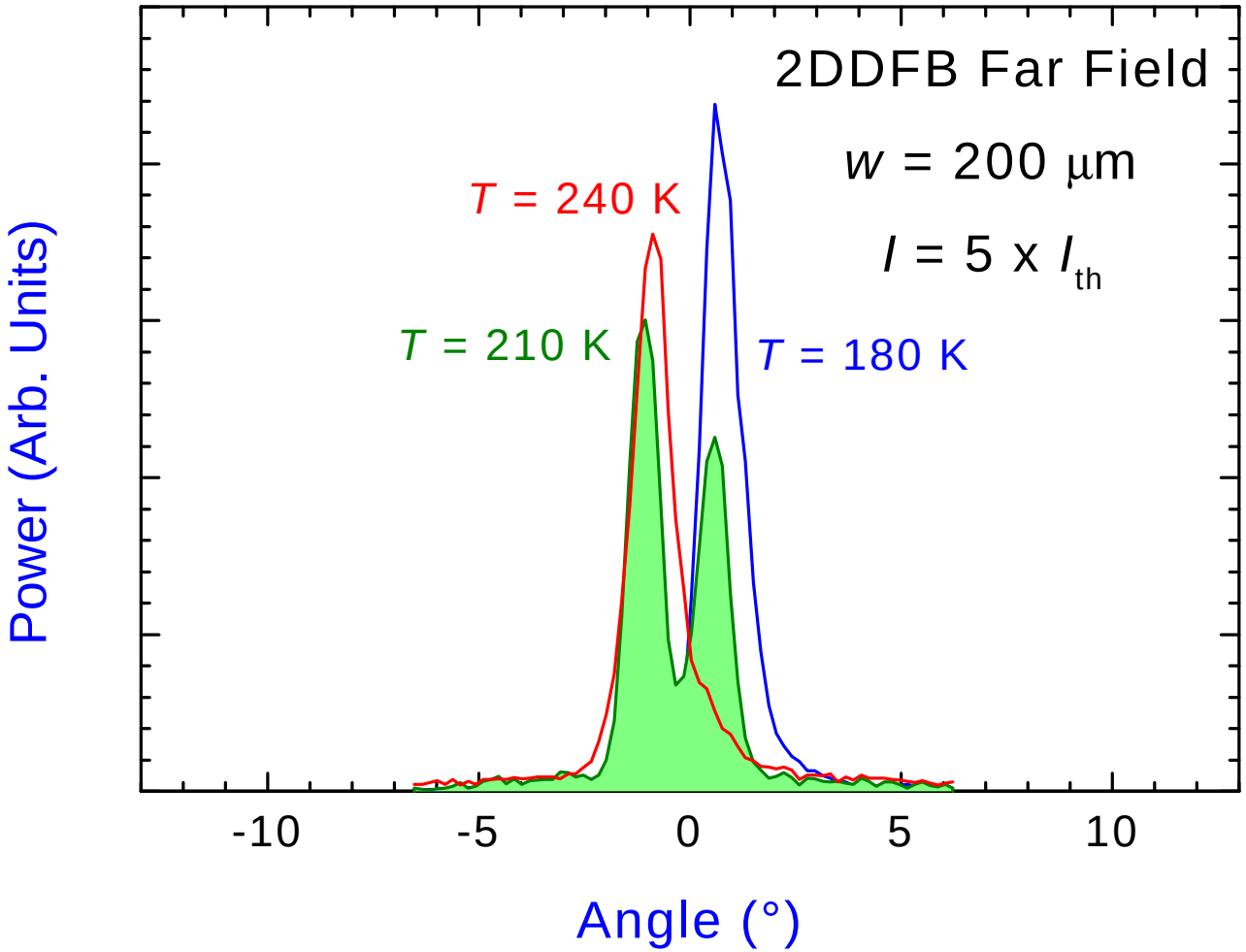
PCDFB efficiency ≈ 30% of Fabry-Perot value – Theory projects 50-60% in optimized structures (α-DFB was 60-70%)

FAR FIELD vs. STRIPE WIDTH



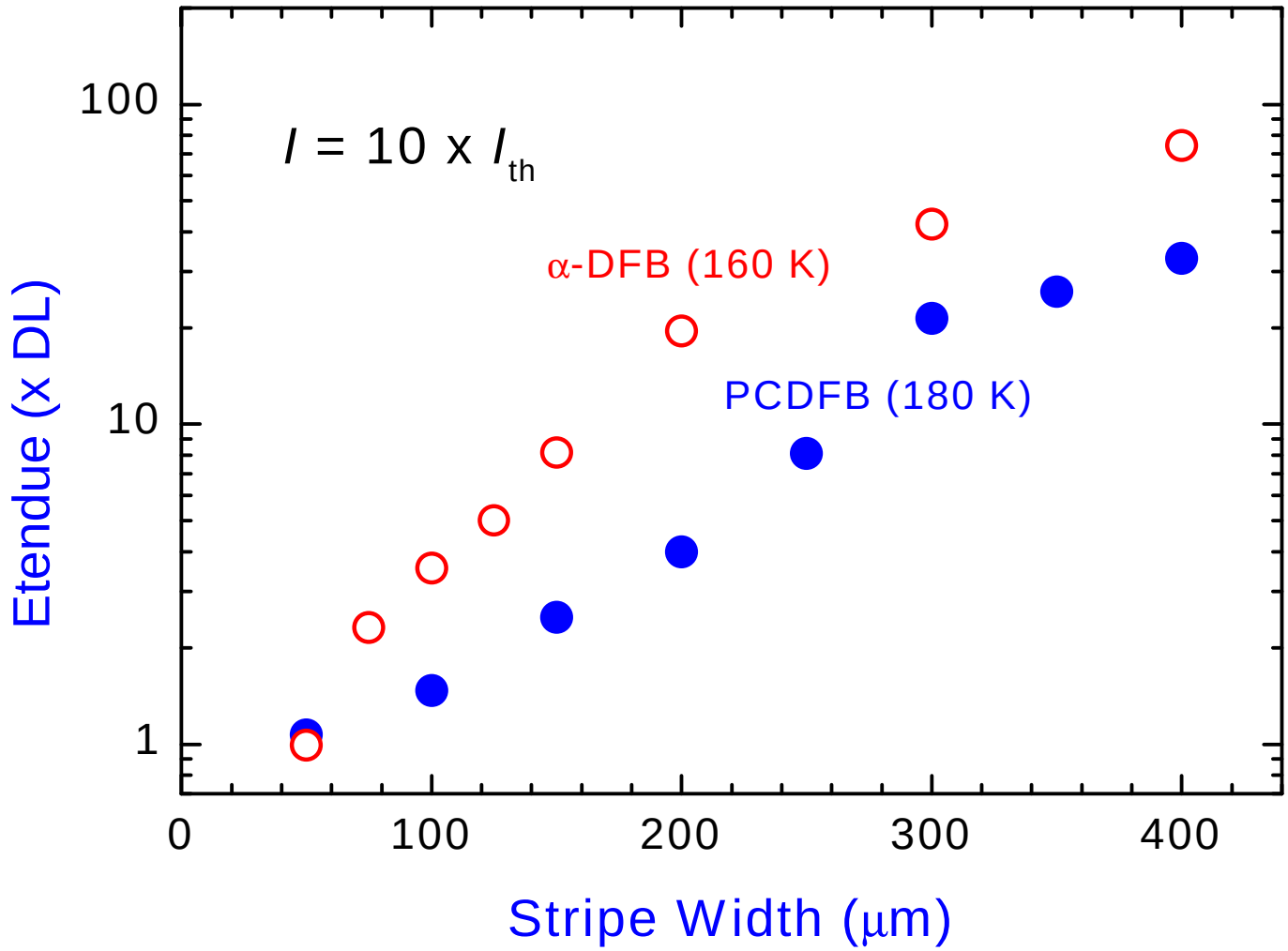
Gradual degradation of beam quality with increasing stripe width

FAR FIELD vs. TEMP (BOTH RESONANCES)



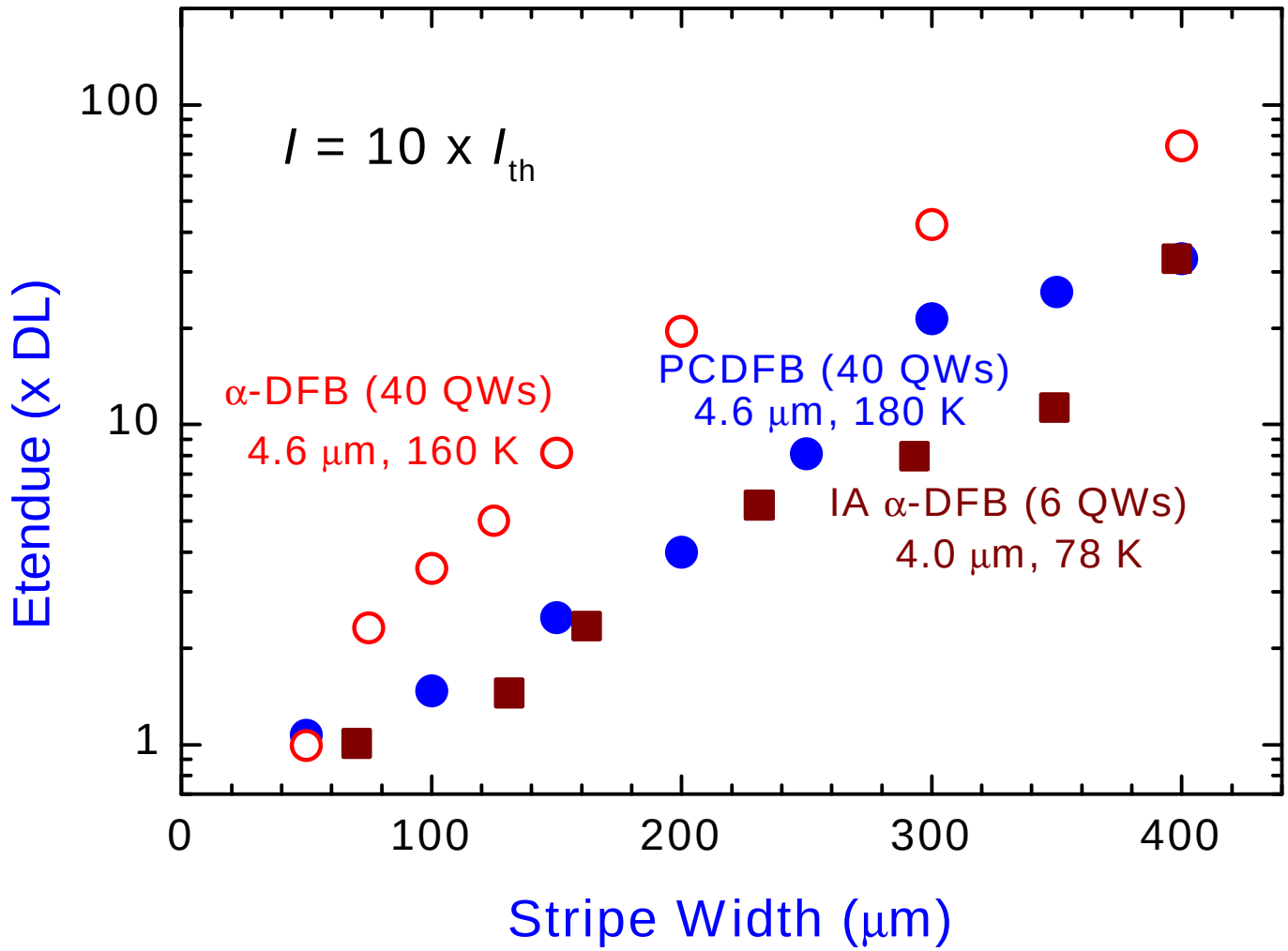
The 2 resonant modes emit either side of zero angle – *Data qualitatively consistent with TDFT predictions, although full understanding will require further investigation*

BEAM QUALITY vs. STRIPE WIDTH



Up to factor of 5 improvement (w = 200 μm) over α-DFBs from same wafer

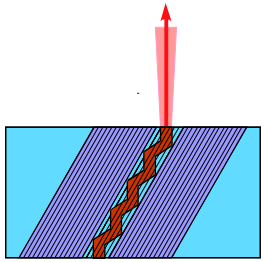
NEW & IMPROVED IA α-DFB



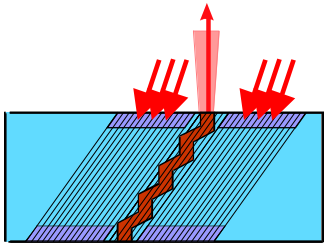
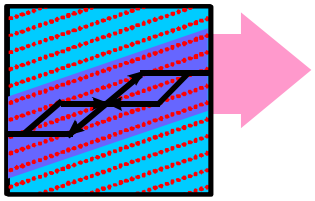
α-DFB from new LL IA wafer displays superior wide-stripe etendue – Implies reduced (internal loss) x (linewidth enhancement factor) product

SUMMARY

- Mid-IR α-DFB
  - Near-diffraction-limited to $w \approx 50$ μm
  - But rapid degradation with increasing w
  - Hardly any spectral narrowing



- Virtual Mesa & Spoiler α-DFBs (Ion bombarded)
  - Both prevent Fabry-Perot-like lasing – Etendue reduced nearly order of magnitude out to $w = 300$ μm
  - But some reduction of efficiency – Net factor of 3 higher brightness



- *Photonic Crystal DFB*
  - Theory projects higher single-mode powers than any other diode approach – *Adaptable to any wavelength*
  - PCDFB laser demo (2nd-order grating) – Substantial spectral narrowing (up to x10), beam quality enhancement (x5) over α-DFB