Proven Performance

High efficiency kW-class QCW 88x nm diode laser bars with passive cooling

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Outline

- **nLight Capabilities Overview**
- **Motivation for 88x nm High Power and High Efficiency Diode Stacks**
- **Performance of 88x nm nLight Bars**
  - CW High Power Operation of 1 cm Bars
  - QCW High Power Operation of 3 mm “Mini Bars”
  - Projected QCW Performance of 1 cm Bars
- **Bar geometry (Marked as CL×BW×FF)**
  - Cavity length (CL): 1.5mm and 3.0mm
  - Bar width (BW): 3mm “mini bars” and 10mm “bars”
  - Fill factor (FF): 50% and 80%
- **Path to Higher Efficiency**
- **Concluding Remarks**

nLIGHT global operations

Vancouver, Washington
- Global headquarters
- Wafer Fab and packaging
- Industrial systems

Germany
- European sales / marketing

Lohja, Finland
- Specialty optical fiber manufacturing and R&D

Sales Reps
- UK
- France
- Italy
- Israel
- Korea
- Taiwan
- Japan
- India
- Australia

Hillsboro, Oregon
- Defense packaging and systems
- R&D and production

Shanghai, China
- High volume packaging
- China sales / marketing

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nLIGHT US operations

- **Vancouver**
  - Established 2000
  - Over 200 employees
  - 6,000 m² manufacturing space
  - 2,200 m² clean room space
  - Functions
    - Wafer fab
    - R&D
    - SG&A
- **Hillsboro**
  - Acquired in 2007
  - Over 50 employees
  - 3,000 m² manufacturing space
  - 1,200 m² clean room space
  - Functions
    - Defense systems
    - Optical, fiber and hybrid packaging

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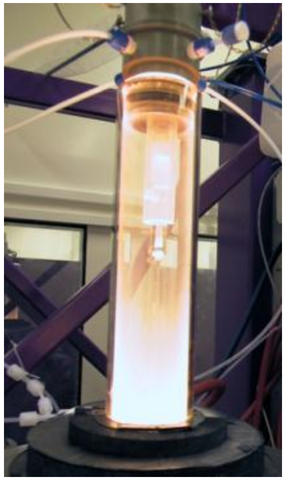
nLIGHT Finland operations

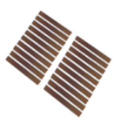
- Acquired in 2007
- 24 employees
- 1,900 m² manufacturing space
- 1,000 m² clean room space
- Functions
  - Fiber R&D
  - Fiber manufacturing
  - Optical engine assembly
  - Test and measurement



nLIGHT's vertical integration supports four key markets

Components	**Lasers**	**Applications**

Diode Lasers



Optical Fiber

Fiber Coupled Diodes

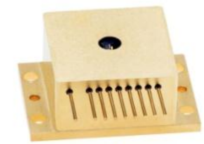
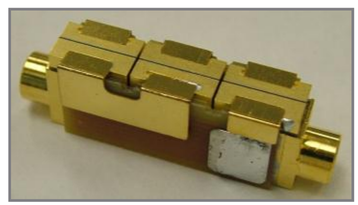
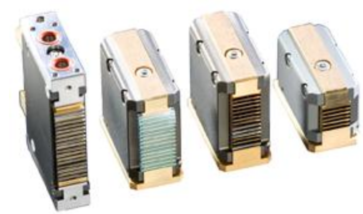
Direct Diode Lasers

Fiber Lasers

Diode Pumped Lasers

- Display / Semi
- Industrial
- Defense
- Medical

nLIGHT's Standard Diode Laser Products

Product category	nLIGHT product platforms
Single Emitter Up to 10W	 
Diode Arrays 10 to 200 Watts	  
Stacks of Arrays 100W to multi-KW	  
Fiber Coupled Packages 15W to 500W	 

nLIGHT provides engineering services to modify COTS packages and assist in product integration, helping to enable critical applications.

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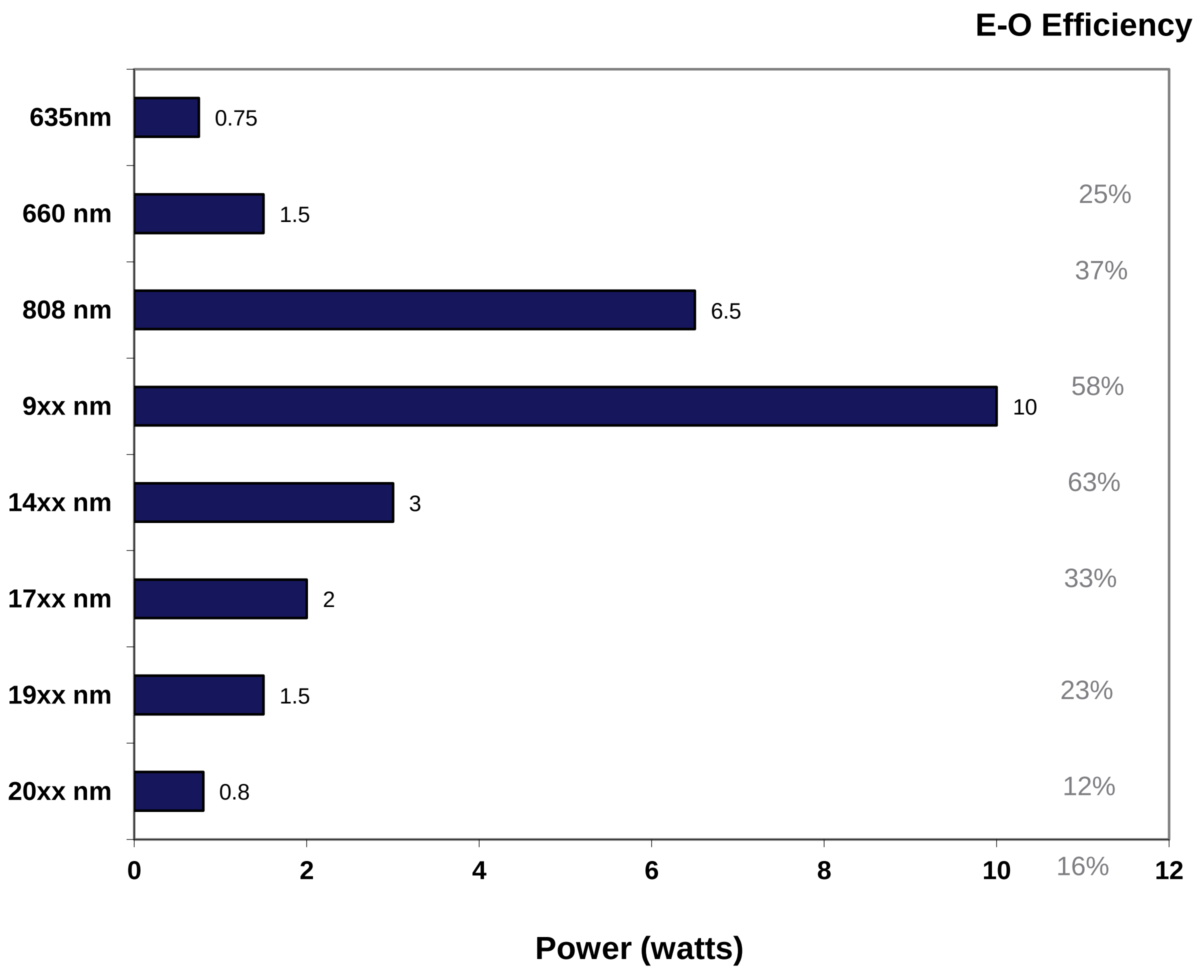
Industry-leading single-emitter performance



* Rated for 2 year operation with <2.5% chips with 20% power drop

Leading Efficiency and Power per single-emitter chip

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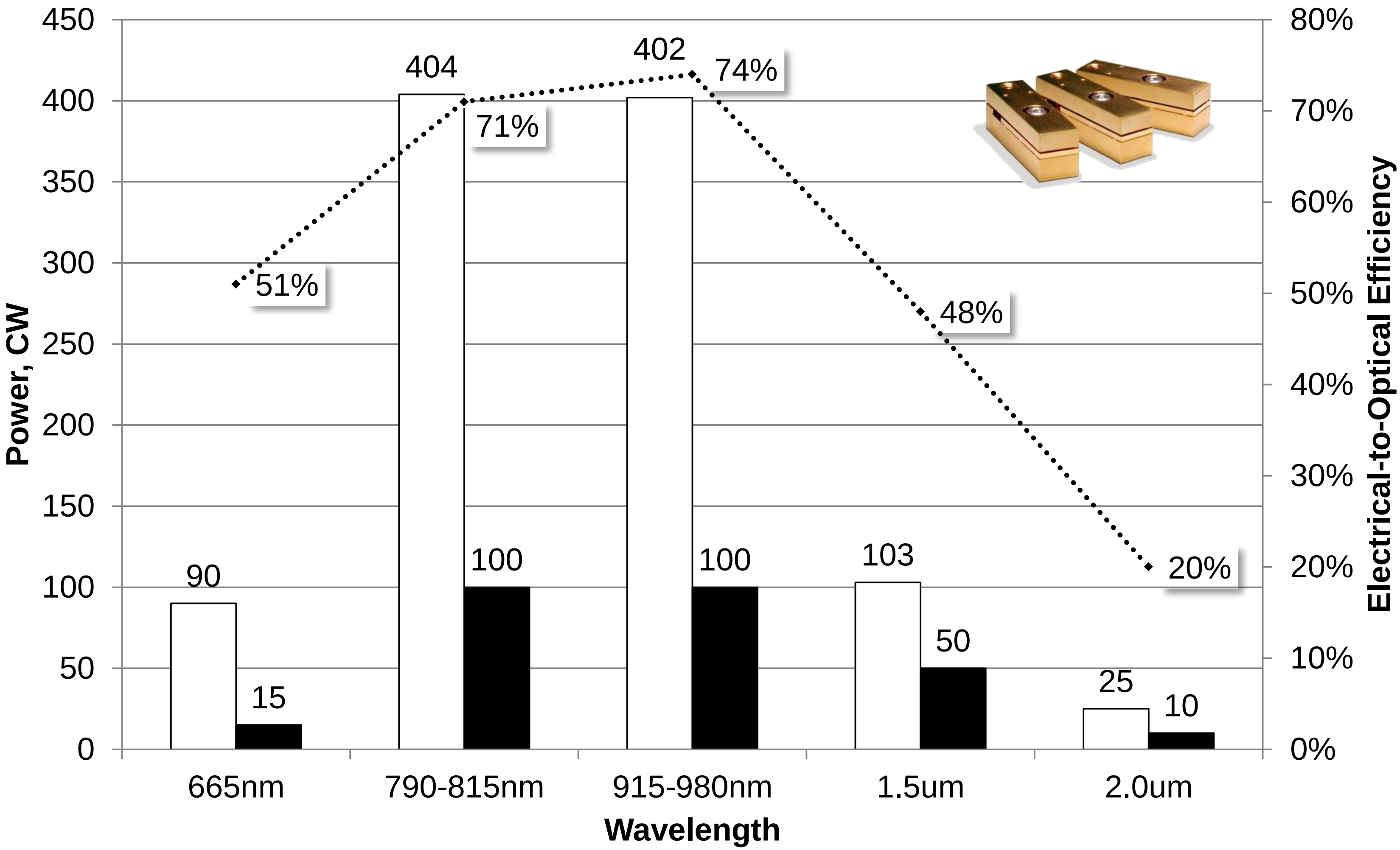
Industry-leading Power and Efficiency Results

Performance results from 1cm-bar CW tested on a micro-channel cooler



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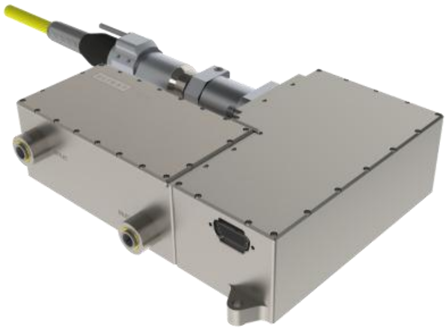
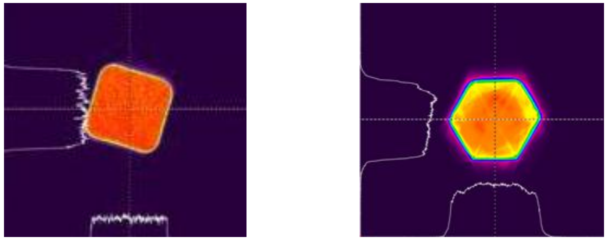
Pearl TKS System

Single-laser subsystems

Process-window™ optics

to 600 W output

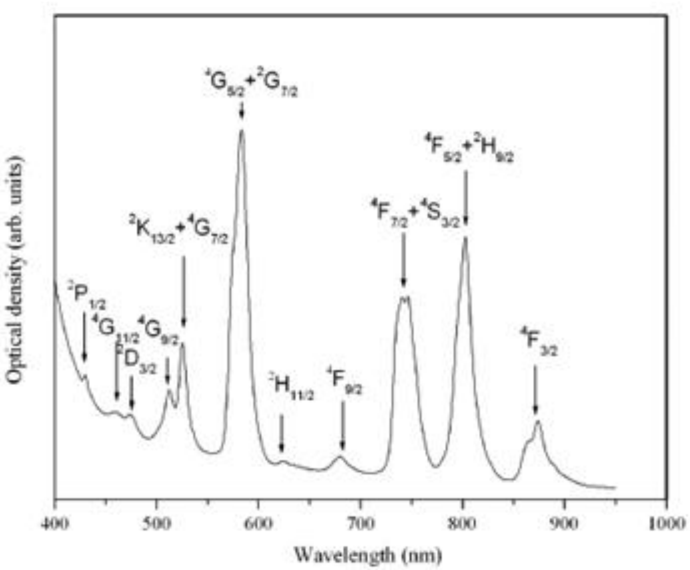


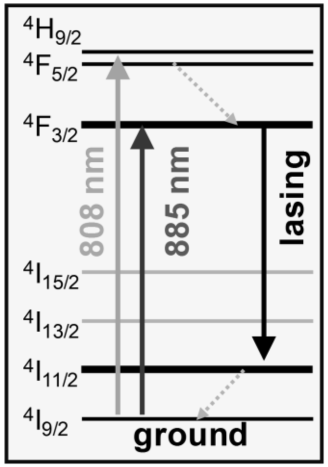


Industrial laser performance for demanding processes.

Pearl-based laser systems that offer industry-leading reliability, optical performance, modulation rates, ease of use.

Motivation for Developing QCW kW 88xnm Bars





Direct bumping Neodymium to $^4F_{3/2}$ state at 885nm

8% Lower Quantum Defect at 88x nm compared to pumping at 808 nm

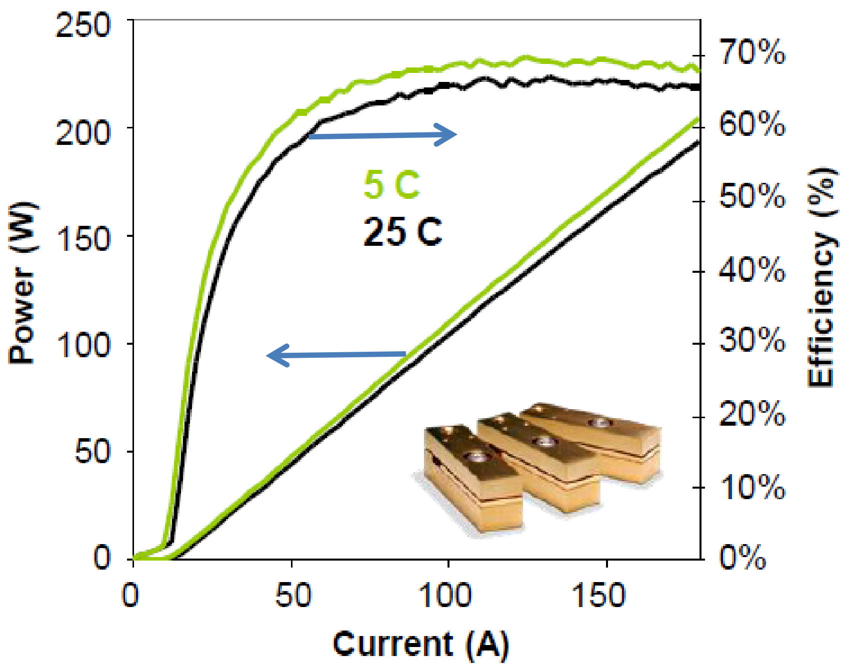
Application requiring high peak powers:

- Laser inertial fusion energy (LIFE)
- Laser range finder (LRF)

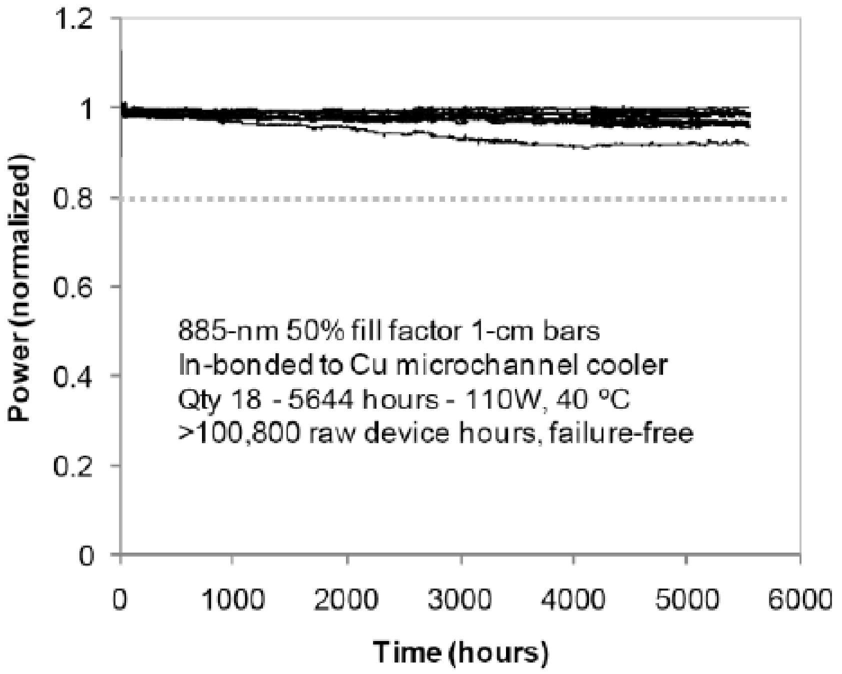
Requirements:

- High peak power/bar
- High reliability
- Lower $/W

nLIGHT's CW 885nm Bars



LIV and efficiency



Reliability

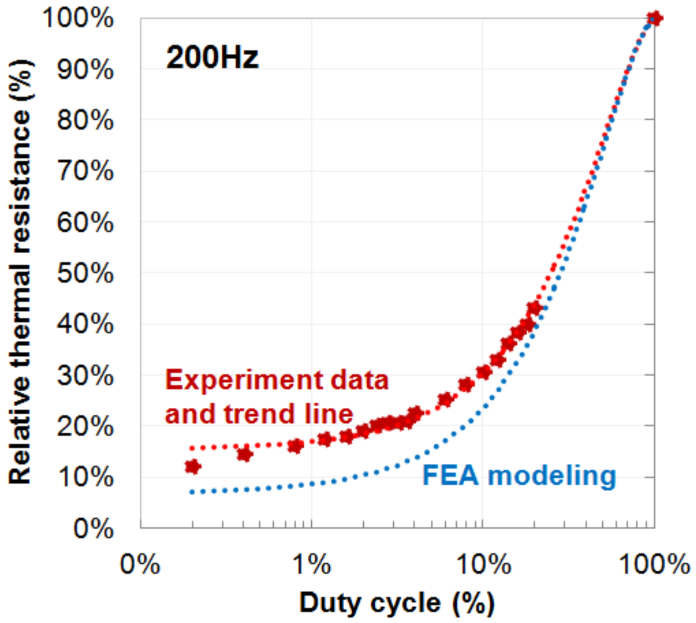
Features:

- Broad waveguide design
- nXLT facet passivated
- Microchannel active cooling
- CW operation

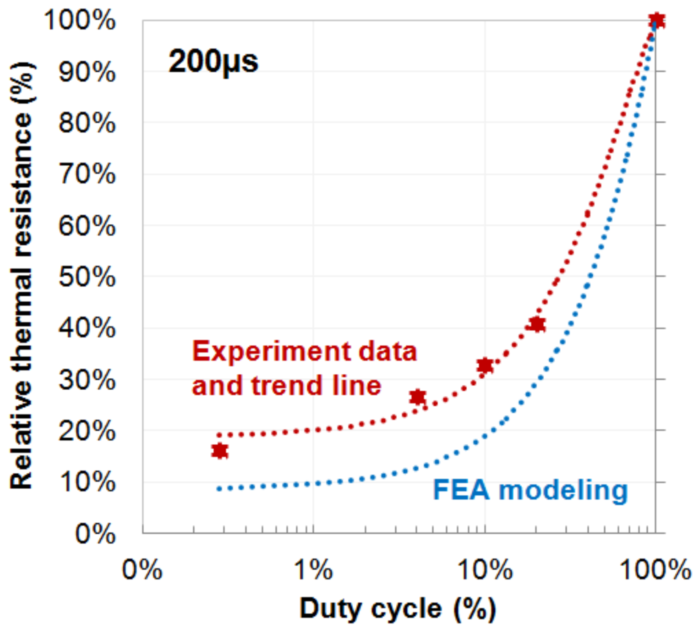
Performance:

- ~200W/bar
- ~70% efficiency
- >5000h operation

Thermal Analysis for QCW/CW Comparison



Fixed repetition rate



Fixed pulse length

Relative Thermal Resistance (%): TR_{QCW}/TR_{CW}

- At low repetition rate and low pulse length QCW thermal resistance is only 10-15% of CW thermal resistance.
- So in QCW mode diode lasers can operate at much higher peak power

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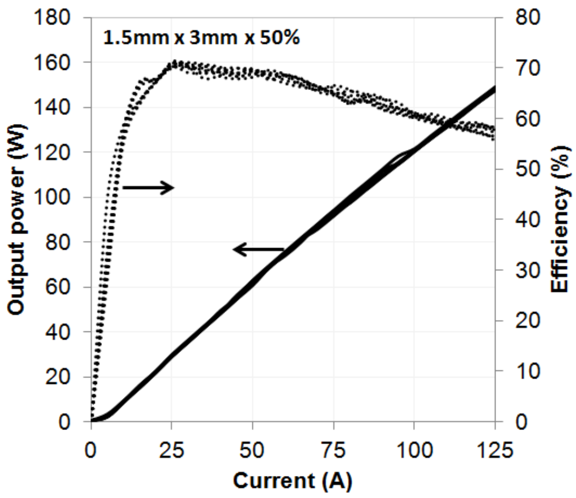
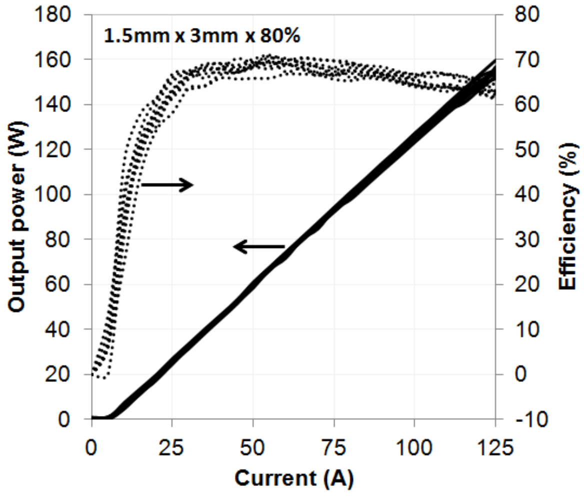
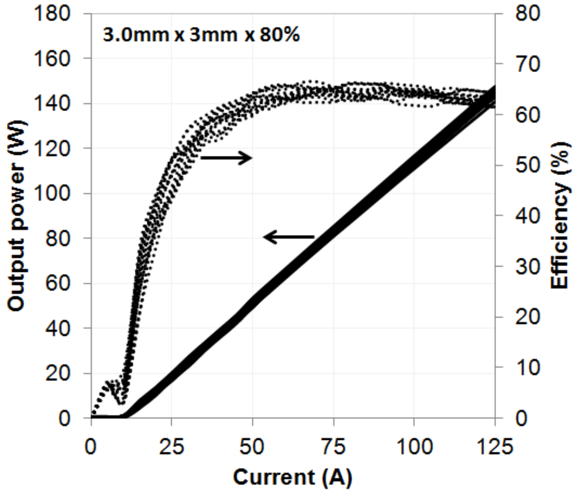
Testing Conditions

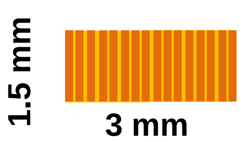
Tests	Characterization	Burn-in test	Accelerated life test
Operation current	Up to 300 A	150 A	150 A
Pulse width	200 µs	200 µs	200 µs
Repetition rate	14 Hz	14 Hz	200 Hz
Duty cycle	0.28%	0.28%	4%
CS base temperature	10-40°C	10°C	20°C
During time	N/A	24 hours (1.2M shots)	6 days (100M shots)

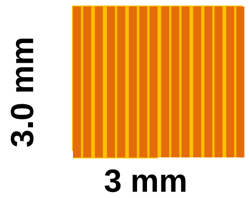
Power and Efficiency of 3mm-wide Mini Bars











Power and efficiency of mini bars up to 125A

(left: 1.5mmx3mmx50%, middle: 1.5mmx3mmx80%, right: 3.0mmx3mmx80%)

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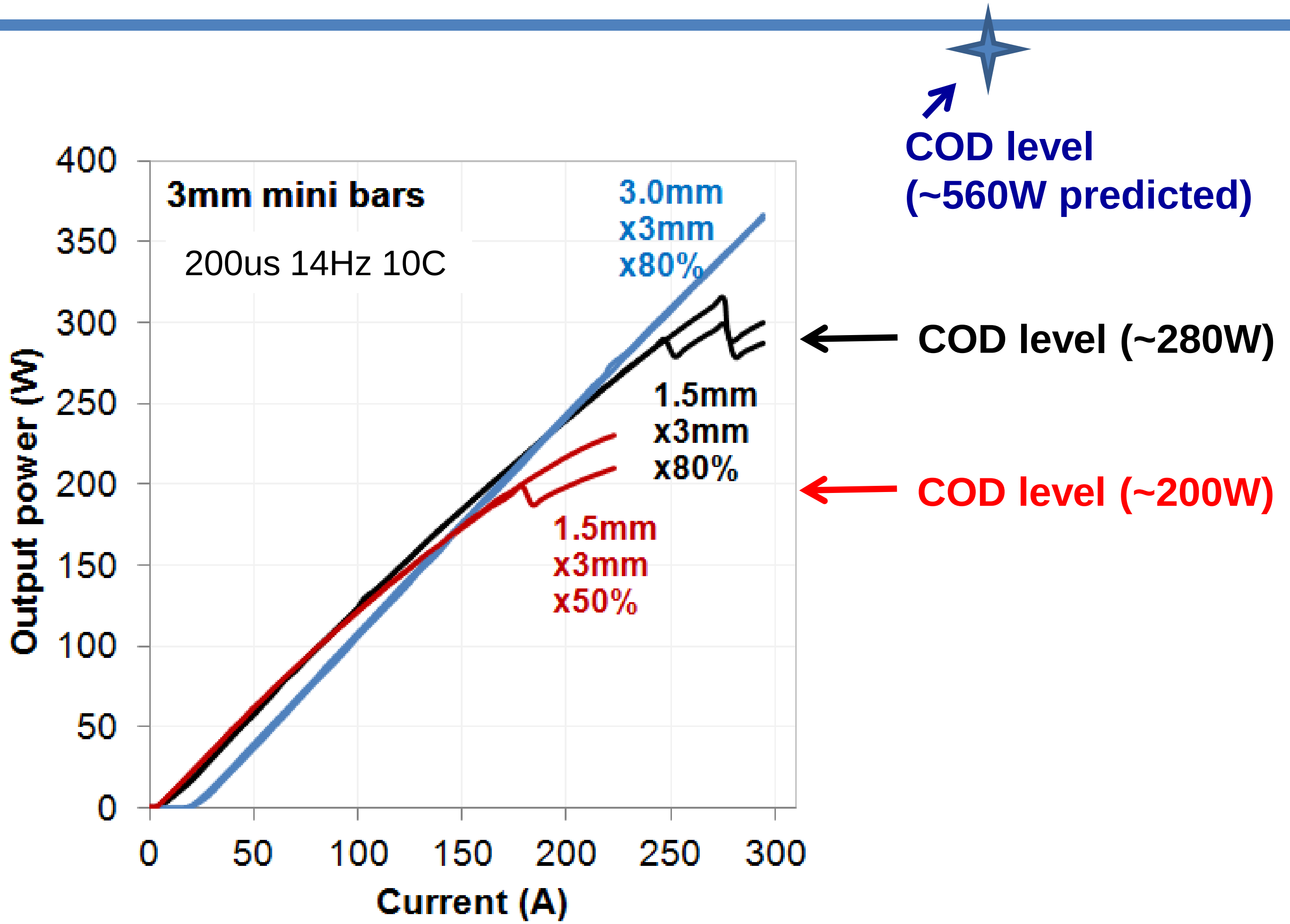
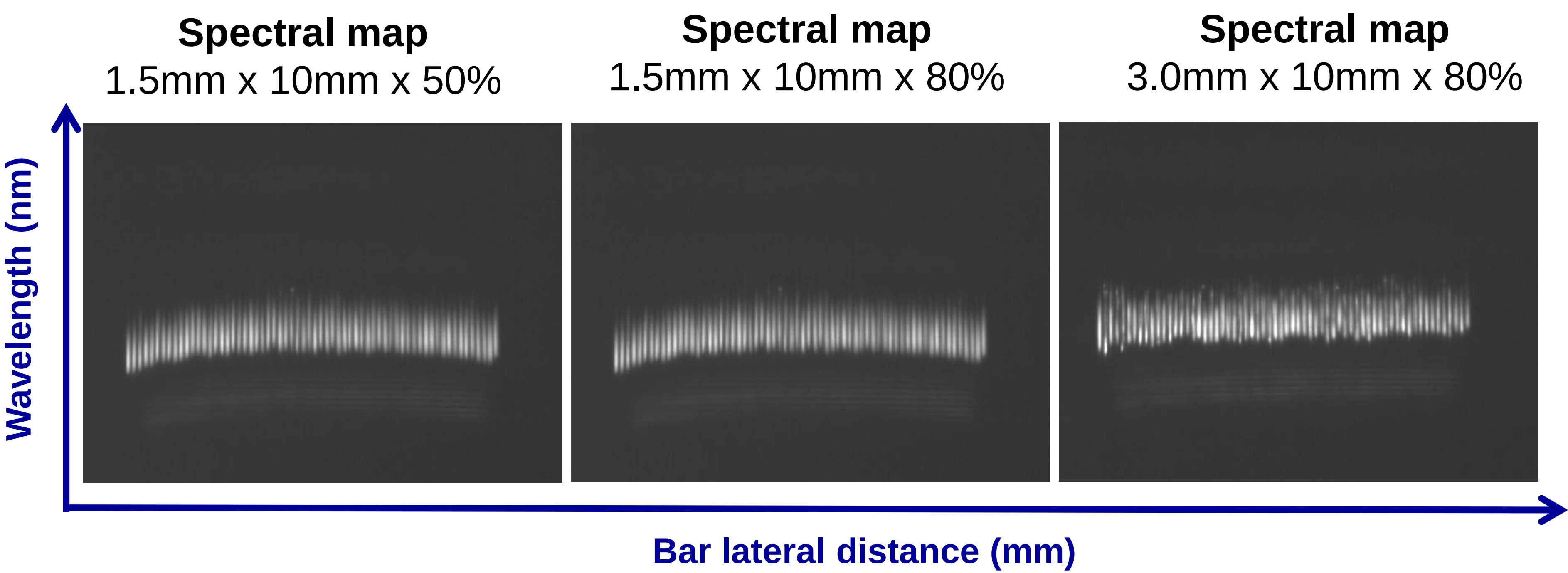
Mini Bars Tests up to 300A



Power of 3mm mini bars

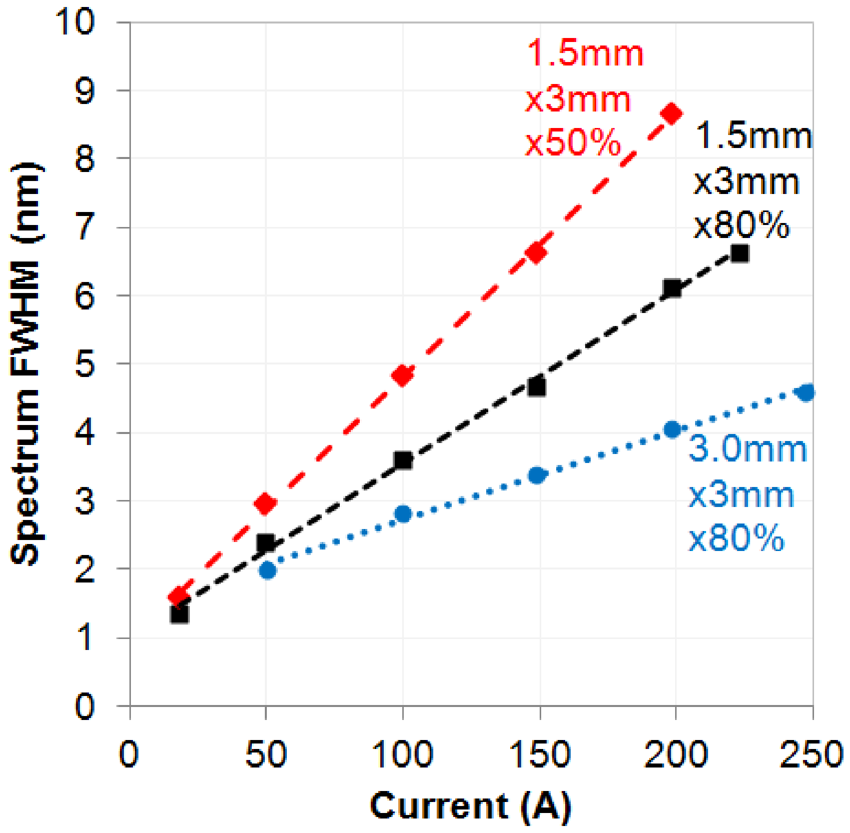
- However, at high currents 3.0mm CL bars show advantages
- 1.5mmCL bars have COD level (not COMD) =<300W, but 3.0mmCL bars have COD level up to 560W predicted

Spectral Maps of 10mm Bars



(All at 125 A)

Spectral Width vs Bar Geometry



Spectral width vs current

Direct spectrum data show that the larger active regions have narrower wavelength width due to smaller thermal resistance

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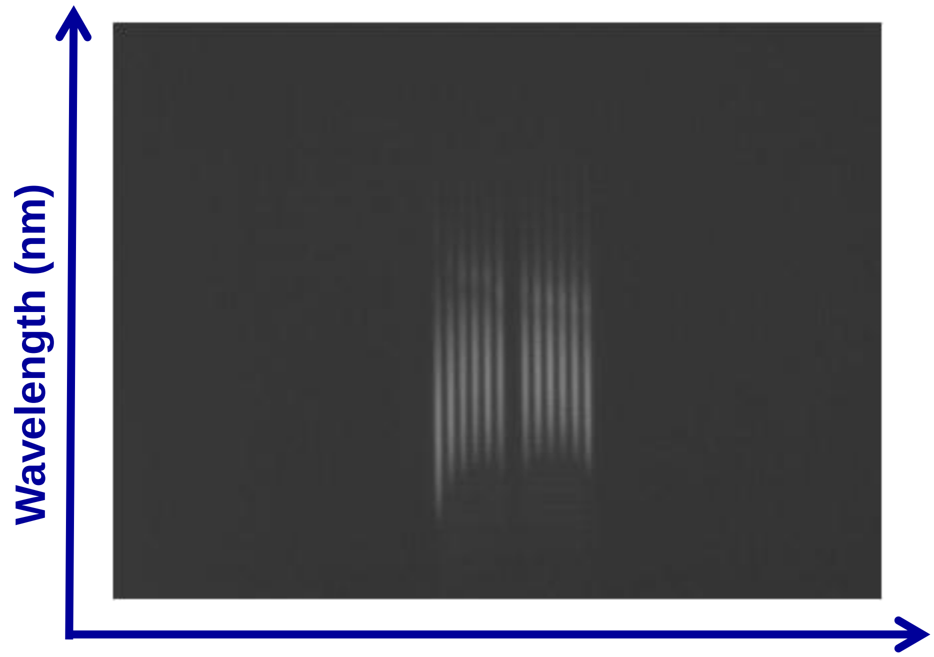
Reliability: Accelerated Life Test



Spectral map

Good reliability:

- After 100 million shots, only one (1) emitter died in all 45 tested minibars, or 1/495(~0.2%) emitter failure rate

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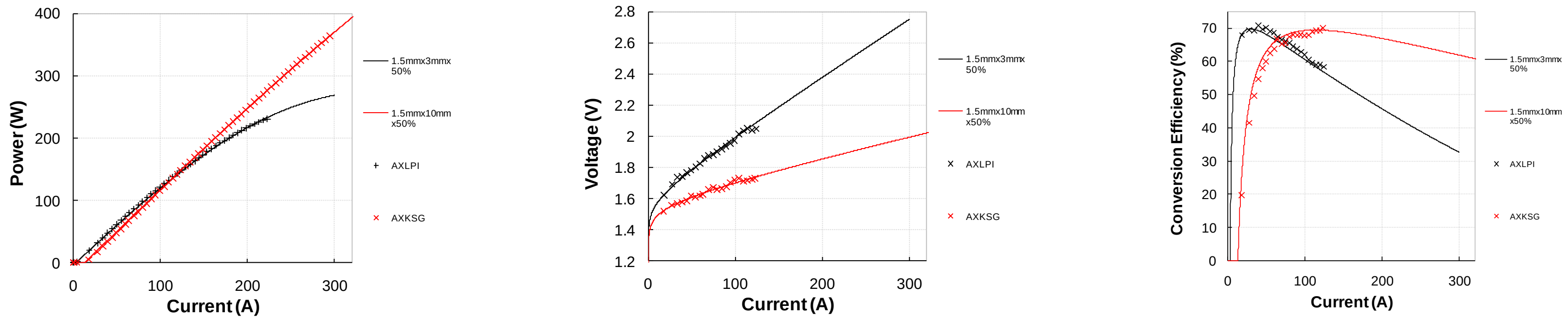
Phenomenological Modeling

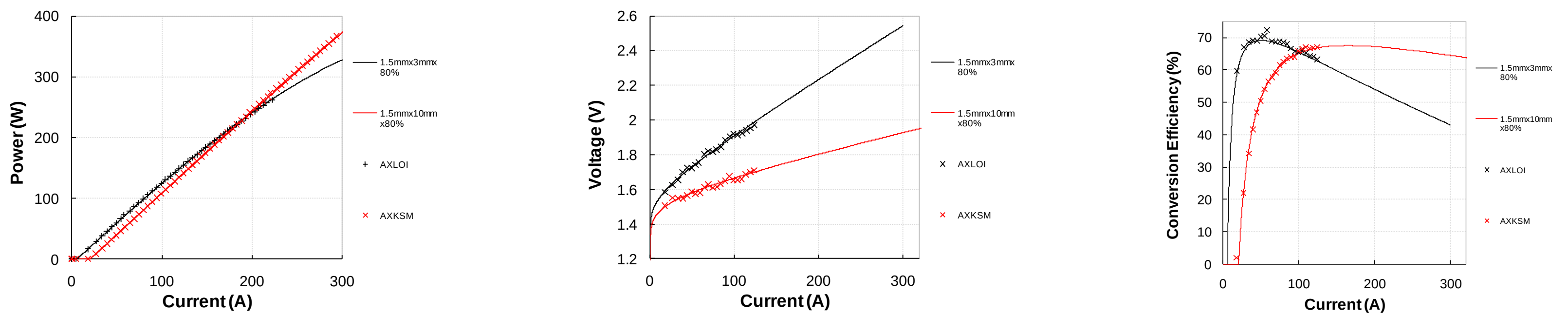
- Rate equation based phenomenological model to describe performance of 3-mm mini bars and 10-mm bars
- Parameters such as internal optical loss and transparency current are adjusted to align modeling results to experimental results
- Model is then extended to predict performance of 10-mm bars at higher operating currents

Model fit to 3mm and 10mm bars

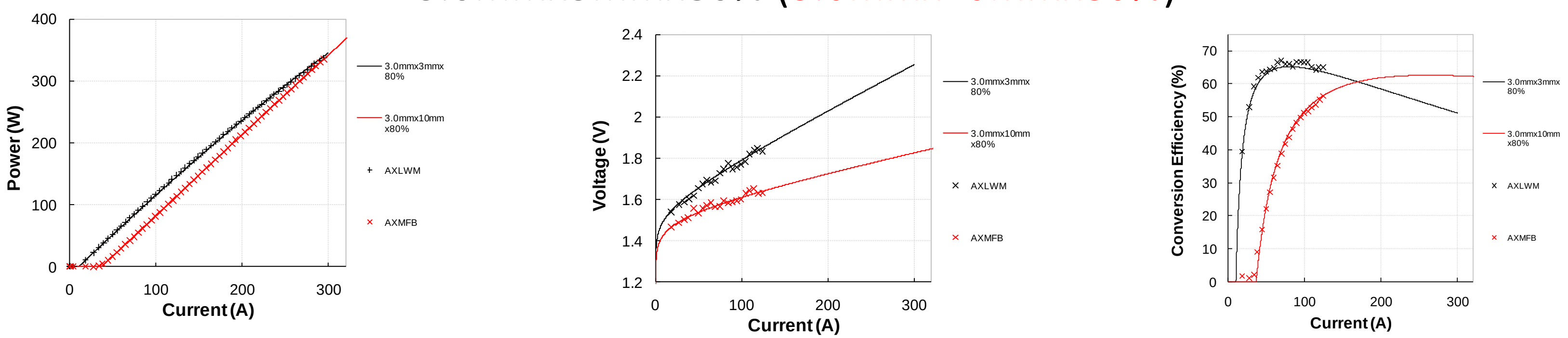
1.5mmx3mmx50% (1.5mmx10mmx50%)



1.5mmx3mmx80% (1.5mmx10mmx80%)



3.0mmx3mmx80% (3.0mmx10mmx80%)



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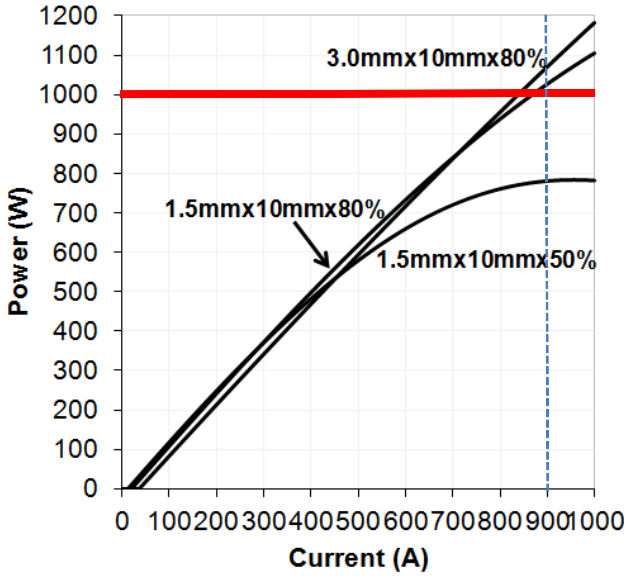
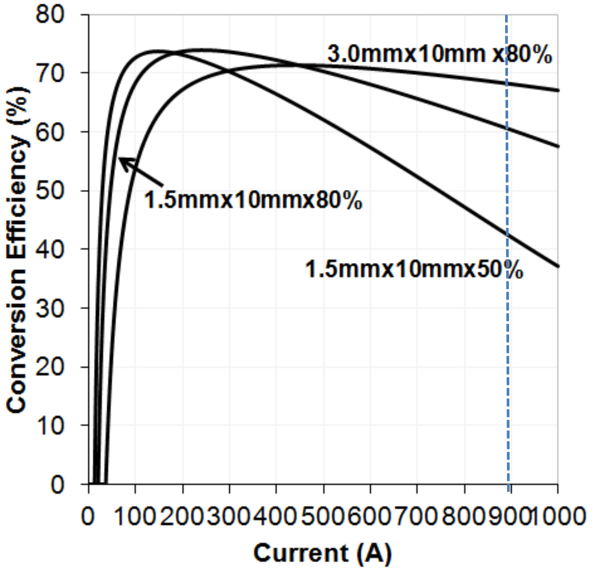
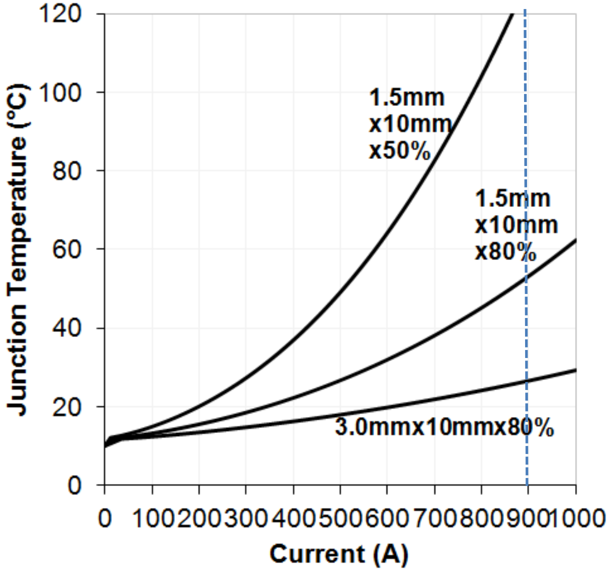
Model Prediction on 10mm Bars



Power



Efficiency



Junction temperature

Bar geometry (CL×BW×FF)	Current at 1kW	Efficiency at 1kW	Junction temperature rise at 1KW
1.5mmx10mmx50%	Only ~750W/bar before thermal rollover, so no data at 1 KW		
1.5mmx10mmx80%	~867 A	~61%	40.4°C
3.0mmx10mmx80%	~838 A	~68%	15.1°C

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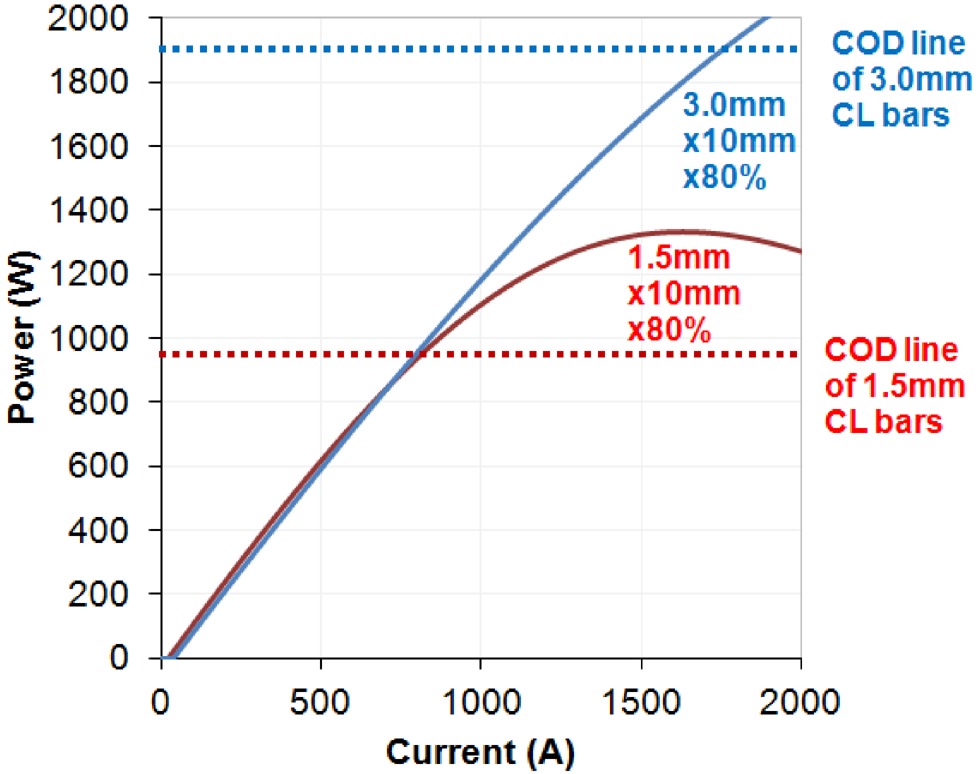
Model Prediction of kW-class Bar Performance



3.0mm CL bars not only makes kW-class bars possible, but also shows superior peak power and lower junction temp

Methods of Achieving Higher PCE

- $\eta_{p,max}$ (PCE) of 975 nm diodes was improved in the DARPA-funded SHEDS Program from 50% to 70% by optimizing V_0, η_{ext}, R_s and I_{th} in Quantum Well gain medium[1,2]

$$\eta_{p,\max} \cong \eta_{ext} \frac{V_F}{V_o}\left(1 - 2\sqrt{R_s I_{th} / V_0}\right)$$

- Further improvement is possible by:
  - Lowering temperature, $\eta_{ext}(T_h)$ → cryogenic ambient
  - Lowering junction temperature, ΔT_j → high thermal conductivity submount
  - Lowering internal loss, α_i → novel gain medium i.e. Quantum Dots

$$\eta_{ext}(T) = \eta_{ext}(T_h)\exp\left(-\frac{\Delta Tj}{T_1}\right)$$

$$\eta_{ext} = \eta_i \frac{\alpha_m}{\alpha_m + \alpha_i}$$

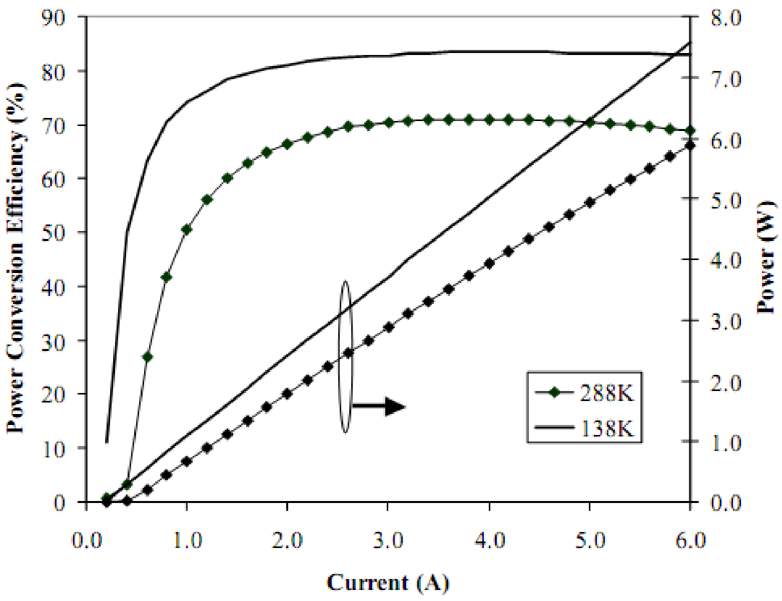
1. M. Kanskar, et. al., "73% CW Power Conversion Efficiency at 50 W from 970 nm Diode Laser Bars", Electronics Letters 41, 245-247 (2005).
2. Paul Crump, et al, ">76% CW Wall-plug Efficiency at High Powers from 0.98-µm Emitting Laser Diodes" Paper #402, ICALEO (2005).

How Much Improvement? Timeline? Risk Factor?

PCE Improving Methods	%Increase	Timeline	Risk	Comments
Cryogenic Temp Operation	15-20% e-o	1-3 yrs	◆	Requires cryo-compatible packaging development
High Thermal Conductivity Submount	3-5% e-o	1-3 yrs	◆	Requires CTE-matched high thermal conductivity material
Low Loss Gain Medium	12-15% e-o	3-5 yrs	◆	Requires non-trivial "ideal" quantum-dot gain medium

Performance of nLight 975 nm Diode at Cryogenic Temperature

- 70% electrical-to-optical power conversion efficiency at 975 nm at ~300K
- ~80% electrical-to-optical power conversion efficiency at 904 nm at ~78K
- Internal quantum efficiency approaches 100% at cryogenic temperatures
- Threshold decreases moderately



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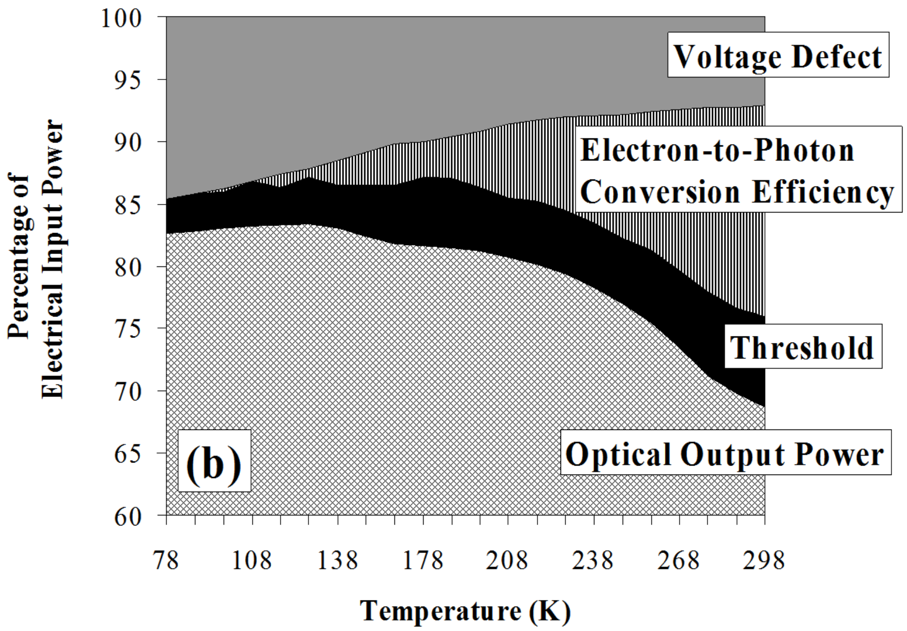
Power Budget for nLight's Cryogenically-cooled 975 nm Diode vs Temp

- Voltage defect increased at cryogenic temperatures
- Diodes optimized for 300K operation show efficiency improvement at lower temperatures ~82% PCE (976 nm diode lased at 904 nm at 77K)
- Full efficiency optimization has not been done for operation at cryogenic temperatures i.e. voltage defect can be improved by designing for 976 nm emission at 77K



Summary

- kW-class QCW bars were fabricated and tested in CS passive cooling packages
- kW-class bar performance with different cavity length and fill factors were explored
- 3mm cavity length bars show advantages in kW power rating, efficiency, and COD levels
- Depending on the application need for power/efficiency/reliability the cavity length can be optimized for the lowest cost
- Cryogenically cooled diodes show potential for >80% electrical-to-optical power conversion efficiency

nLIGHT Proven Performance

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Thank You!