Diode Laser Efficiency Increases, Enables > 400-W Peak Power from 1-cm Bars, Shows Clear Path to Peak Powers in Excess of 1-kW

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  • This material is approved for public release, distribution unlimited
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• Work to improve $/W through increased power per bar is supported by AFRL under contract number: FA9451-04-D-0354
Contents

• nLight Overview

• Survey of peak bar performance across wavelength

• Projected path to increased power

• Experimental progress
  – Includes update on high efficiency devices

• Cryogenic Results

• Conclusions
nLight Overview

- **History**
  - Founded in 2000
  - Over 100 employees

- **Technology**
  - High power laser diodes from 630 to 1900 nm
  - Broad range of packages

- **Production**
  - 60,000 sq ft vertically integrated manufacturing facility
  - Complete capabilities with MOCVD through packaging
nLight’s products range from several Watts to several tens of kW

<table>
<thead>
<tr>
<th>Product category</th>
<th>nLight product examples</th>
</tr>
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<tbody>
<tr>
<td>Single Emitter</td>
<td></td>
</tr>
<tr>
<td>Up to 7W</td>
<td></td>
</tr>
<tr>
<td>Diode Arrays</td>
<td></td>
</tr>
<tr>
<td>40 to 100 Watts</td>
<td></td>
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<tr>
<td>Stacks of Arrays</td>
<td></td>
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<tr>
<td>&gt;100W to many kW</td>
<td></td>
</tr>
<tr>
<td>Fiber Bundled Arrays</td>
<td></td>
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<td>&lt; 40 Watts</td>
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Diode Laser Bar Performance And Cost Rapidly Improving

As power level per bar increases, $/W falls
Segmentation of Market for Laser Material Processing

The diagram illustrates various applications of laser material processing, categorized by laser power and beam parameter product ($\theta_0 w_0$). Key applications include:

- **Polynomial Welding**
- **Cutting non-metals**
- **Heat Cond Welding**
- **Brazing**
- **Cladding**
- **Deep Penetration Welding**
- **Hardening Remelting**
- **Cutting**
- **Printing Technology**
- **Soldering**
- **Drilling**
- **Marking**

The limit of today's diode lasers is indicated by the red line on the graph.
Single Emitters Allow Access to All These Markets

State of the art single emitters

Combine physically into bars*

Combine optically

* The focus in this presentation
DOD and Industrial Market Have Same Goal

100kW Laser weapons
Water Cooled Micro-channel Heatsinks for Maximum Reliable Power
Temperature Control Enables Reliable 125W Operation

Data for design with 364-W peak power

Rule of thumb – reliable power ~ 1/3 to 1/2 peak
Bars Combined in Stacked Arrays for > 1.6kW CW Output

> 500W/cm² CW output power density directly from stack
Integrated Spectral Width < 2.2nm to High Temperature

![Graph showing integrated spectral width](image)
Single Bars Deliver > 400W from 800-nm to 980-nm

80% fill factor, 3-mm cavity
Water-cooled copper micro-channel
90W from single 660-nm Diode Laser Bar

![Graph showing output power and efficiency versus current.](image)

- **Output Power (W)**: The graph plots the output power in watts against the current in amperes.
- **Efficiency (%)**: The graph shows the efficiency in percent against the current in amperes.

- **Key Points**:
  - **10C 0.5-lpm**
  - **30% fill, 1-mm cavity length**

This graph illustrates the performance characteristics of a 660-nm Diode Laser Bar, highlighting the relationship between current and output power along with the efficiency under specified conditions.
103W from single 1470-nm Diode Laser Bar

Diagram showing the relationship between output power (W) and current (A) with a peak output of 103 W at 100 A for 20°C water cooling.
23.5W from single 1900-nm Diode Laser Bar

Output Power (W)

Efficiency (%)

Current (A)

5C water 0.5-lpm
Peak Performance Summary

![Graph showing peak efficiency and peak bar power vs wavelength (nm)]

- **Efficiency (%)**
- **Peak Bar Power (W)**
- **Wavelength (nm)**

Graph lines:
- **Peak Efficiency**
- **Peak Bar Power**
Extrapolate Maximum Achievable Power

\[ P(I) := \eta_d(T) \cdot (I - I_{th}(T)) \]

\[ P(I) := \eta_d \cdot \exp\left[\frac{-R_{th} \cdot \left(\frac{I \cdot V_0 + V_d}{T_1} - P\right)}{T_1}\right] \cdot \left[I - I_{th} \cdot \exp\left[\frac{-R_{th} \cdot \left(\frac{I \cdot V_0 + V_d}{T_0} - P\right)}{T_0}\right]\right]^* \]

Extrapolate > 1kW Per 1-cm Bar

- 80% + 0.14C/W
- 76% + 0.2C/W
- Fitted Measured
Junction Temperature Control Increases Peak Power

Graph showing the relationship between output power (W) and junction temperature (°C), with fitted and measured points. The graph includes lines for 76% + 0.2°C/W and 80% + 0.14°C/W.
### Key Parameters for Delivering 1-kW Bar

<table>
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Key Term: Voltage Defect

No voltage

Minimum voltage for lasing

Minimum voltage is band-gap of quantum well
Any more is called the “voltage defect”
Low Defect from 850-nm to 980nm

Conventional Laser

SHEDs 975-nm

SHEDs 875-nm
High Peak Efficiency from 850-nm to 980nm

![Graph showing high peak efficiency from 850-nm to 980nm. The x-axis represents wavelength (nm) ranging from 840 to 990, and the y-axis represents efficiency (%) ranging from 0 to 75. The graph indicates a consistent efficiency across the specified wavelength range.]
71% Peak Efficiency from 900-nm to 965-nm

Light (W)

Efficiency (%)

Current (A)

900-nm

965-nm
980-nm Bars Deliver 100-W Output at 73% Efficiency

![Graph showing output power vs. current and efficiency vs. current for 980-nm bars. The graph includes a curve for output power and another for efficiency. The legend indicates 5C water 0.5-lpm.]
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Waste heat Increases for High Power Bars

![Graph showing waste heat increases vs output power with fitted and measured data points.]

- **Fitted**: 76% + 0.2C/W
- **Measured**: 80% + 0.14C/W

Graph axes:
- **Output Power (W)**
- **Waste Heat (W)**
Improved Thermal Resistance Increases Peak Power

![Graph showing improved thermal resistance increasing peak power with current. The graph compares 1-mm (20% Fill) and 4-mm (80% Fill) fill levels, with power (W) on the y-axis and current (A) on the x-axis. The graph illustrates a significant increase in power with increased current for both fill levels.](image-url)
Material Efficiency Degraded for Large Device Lengths

25°C on c-mount
200-µm stripe
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Passivated Single Emitter Achieves High Power Density

7-W peak power

800-nm
10-°C c-mount
50-µm stripe 1.5-mm cavity
Passivated Bar Achieves High Power Density

Equivalent to 800W per bar for 80% fill factor

20% fill factor 1-mm cavity
70% efficient, 203W
5 °C 0.5-lpm
975-nm
Data Clearly Indicates 1kW Bar is Achievable

- 808-nm Single emitter
- 980-nm bar
- Expected high fill factor

Rollover Power (W):
- 10 - 1000
- 100 - 10000
- 1000 - 100000
- 10000 - 1000000

Power / emitting aperture (mW/um):
- 0 - 20
- 20 - 100
- 100 - 140
- 140 - 160
- 160 - 180
- 180 - 200
Conclusions

• High performance over wide wavelength range
  – 90-W at 660-nm, 23.5W at 1900-nm
  – 400W from 800-nm to 980-nm

• High Efficiency from 850-nm to 980-nm
  – Bars, single emitters > 65% efficiency product release

• Project 1-kW peak per bar (~ 300W reliable per bar)
  – Good progress against major limitations

• Future is getting brighter!