Cryolaser:
Innovative cryogenic diode laser bars optimized for emerging ultra-high-power laser applications

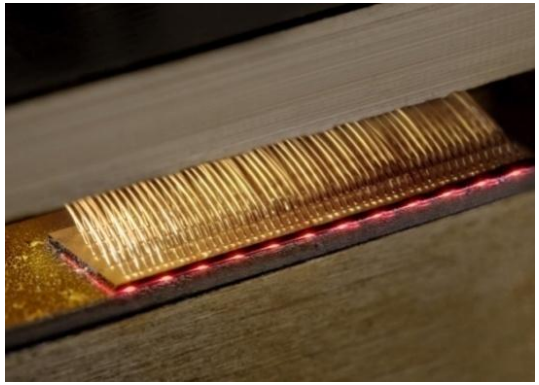
P. Crump, C. Frevert, H. Wenzel, G. Erbert and G. Tränkle

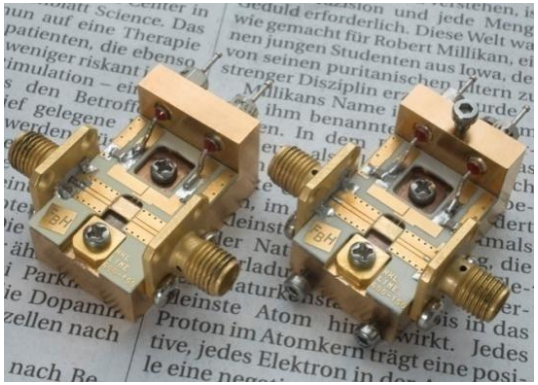
Contents

Contents

FBH: world-wide recognized technology center

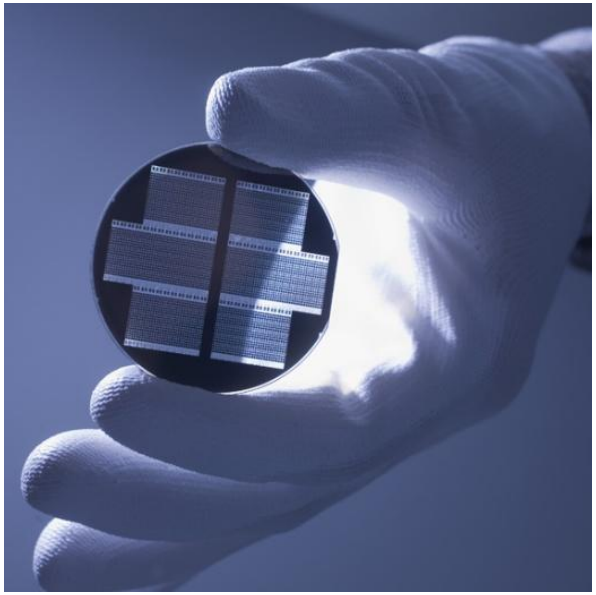
- International center for MMICs and high-power diode lasers
  - covering all competencies: design, epitaxy, wafer process, characterization, qualification
- Full value chain: from design to modules to manufacturing of pilot series
- Successful track record in knowledge and technology transfer of innovative product ideas and technologies:
  - Strategic partnership with industry (Jenoptik, Trumpf, TESAT Spacecom….)
  - Successful university cooperation model (Technische Uni Berlin, Humboldt Uni Berlin …)
  - Founder of spin-offs (Jenoptik Diode Lab, eagleyard Photonics, Lumics …)



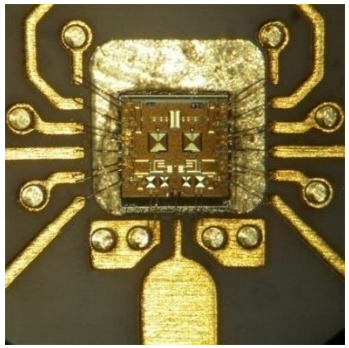


FBH: Mission

- Applied research and development on III-V semiconductor devices, circuits and modules for microwave technology and optoelectronics
  - Close cooperation with universities, research institutes and enterprises
  - Technology transfer
  - Customer- and service-focused
  - Part of value chains
  - Beyond demonstrators: pilot & small-scale series
  - Academic and industrial education & training



Facts & Figures

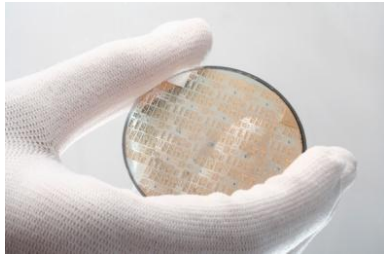


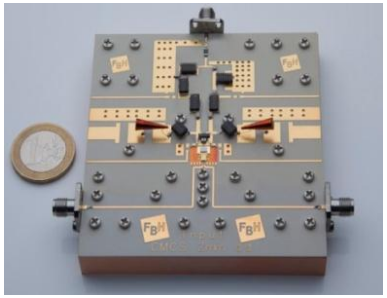
- **F**erdinand-**B**raun-Institut, Leibniz-Institut für **H**öchstfrequenztechnik (FBH)
- Institute within Forschungsverbund Berlin e.V., member of the Leibniz Association
- Located in Berlin, Germany
- Shareholders
  - State of Berlin / Federal Republic of Germany
- Founded in 1992
- ~ 240 Staff (including 125 scientists & PhD students)
- Academic partners include:
  - Technische Universität Berlin
  - Humboldt-Universität zu Berlin
  - Goethe-Universität Frankfurt am Main
- Quality assurance
  - ESA-qualified for applications in space
  - Integrated management system (quality, environment, occupational health & safety)

GL ISO 9001 ISO 14001 OHSAS 18001
GL Systems Certification

Leibniz Ferdinand-Braun-Institut

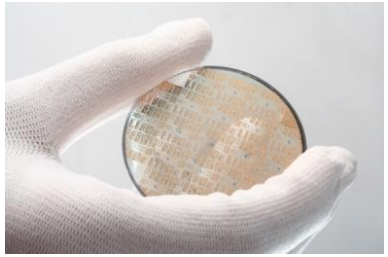
Research program

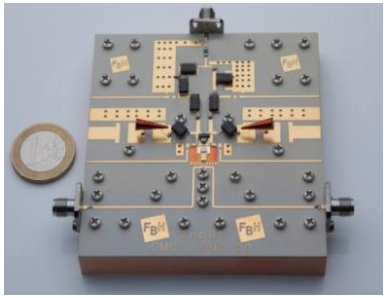




- Microwave components & systems
  - GaN FETs & MMICs
  - MMICs for frontends up to 100 GHz
  - 100+ GHz: THz electronics (InP HBT)
  - Microwave plasmas
- GaN power electronics
  - FETs & diodes up to 1000 V
- GaAs diode lasers
  - High-power diode lasers (0.63 - 1.2 µm)
  - Hybrid diode laser systems (rgb)
  - Laser sensors & metrology
- GaN LEDs and GaN diode lasers
  - UV & true blue
- III-V semiconductor technology
  - Epitaxy & process technology
  - Mounting & packaging

Research program





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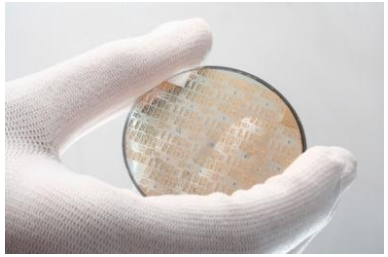

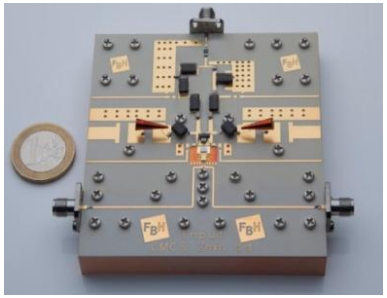

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For compact, efficient pulsers?

Contents

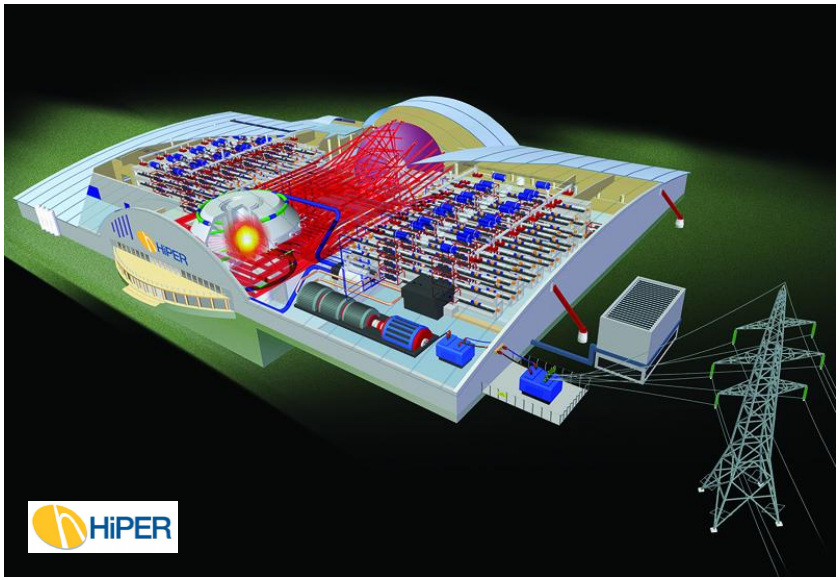
Contents

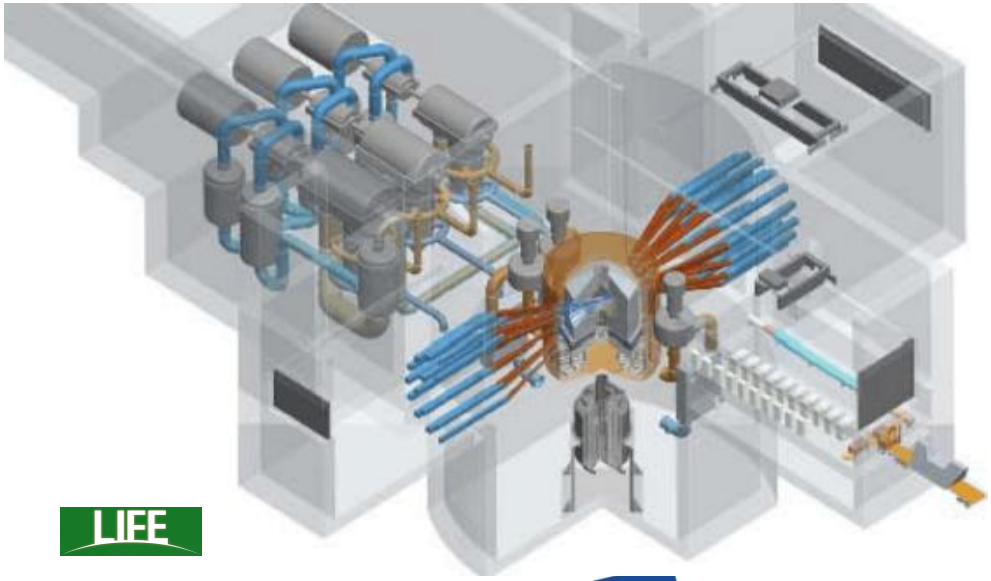
Motivation: help enable power generation via HEC-DPSSL

- A new generation of high-energy-class laser systems are in development
  - For example, LIFE and HiPER, using LIF as a low-carbon energy source

- Alternative HEC-DPSSL system architectures in preparatory phase
  - LIFE using Nd-doped gain media, pumped at ~872nm (~ 100-500µs)
  - HiPER using Yb-doped gain media, pumped at ~940nm (~ 1-2ms)

- Improved components needed to reach full performance targets





Challenge: need ultra-high performance diode lasers

- LIF needs diode lasers to deliver high density of ”useful photons“ at very high efficiency
  - Diode lasers generate all the optical energy in the system:
    - high efficiency crucial for high “net power out“
  - Solid state lasers must be appropriately pumped (“useful photons”):
    - at a precise wavelength (872nm for Nd:YAG, 940nm for Yb:YAG)
    - at sufficiently high power density
- These ultra-high performance sources do not currently exist

Parameter	**State of the art QCW Bars**	**LIFE Targets** [4]
Optical power density	> 10 kW/cm^2 [1,2]	> 25 kW/cm^2
Power conversion efficiency at the operating point	> 65% [1,3]	> 75%

- Massive cost reduction also needed (target: < 0.01 €/W) [4]

[1] A. Kohl *et al.* Proc. SPIE 7835, 78350Q (2010)

[2] J Junghans *et al.* Proc. SPIE 8241, 82410E (2012)

[3] J. G. Bai *et al.* Proc. SPIE 8241, 82410W (2012)

[4] R. Feeler *et al.* Proc. SPIE 7916, 791608 (2011).

Program goal: step-improvement in diode lasers for LIF

- Goal: develop novel diode laser technology that can fulfil LIF goals
- Approach: Leverage diode temperatures < 0°C to enable performance step-change

Parameter	**State of the art QCW Bars**	**Program goals**
Optical power per bar	~ 300W (commercial) [1,2] ~ 1kW (lab) [3,4]	> 1.6 kW
Power conversion efficiency at the operating point, η_E	> 65% [1,3]	> 80%
Spectral width (95% power)	> 5 nm	< 1 nm
Heatsink temperature	295 K	200K

- Cost reduction (€/W) via high power per bar, internal gratings

[1] A. Kohl *et al.* Proc. SPIE 7835, 78350Q (2010)

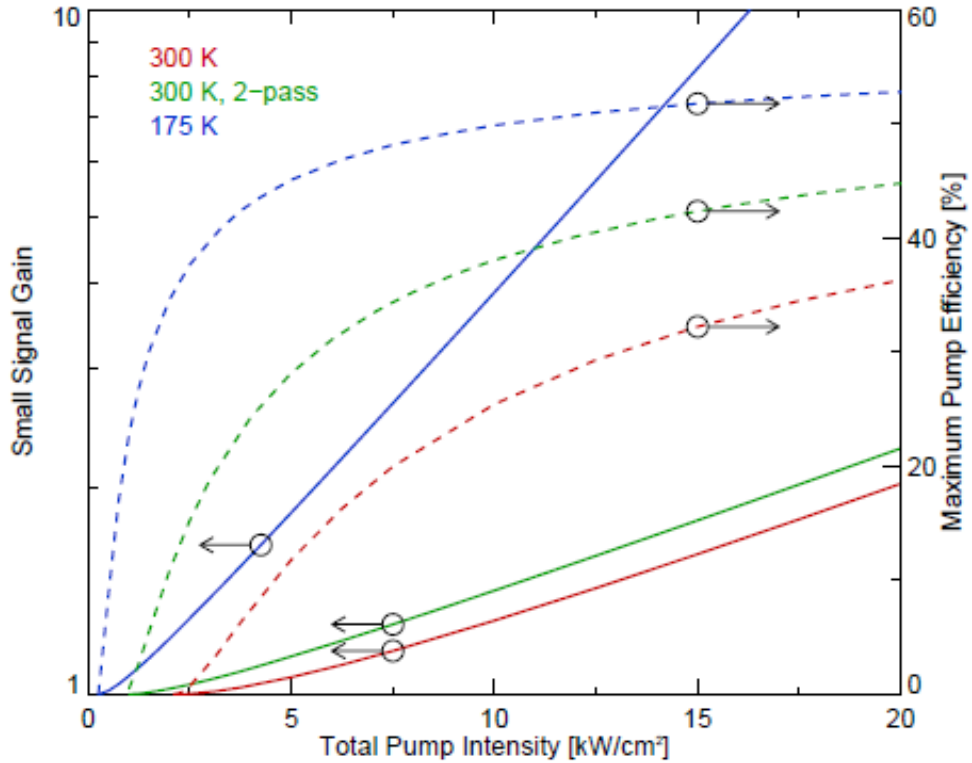
[2] E. Deichsel *et al.* Proc. SPIE 6876 68760K (2008)

[3] J. G. Bai *et al.* Proc. SPIE 8241, 82410W (2012)

[4] D. Schröder *et al.* Proc. SPIE 6456, 64560N (2007).

T < 0°C beneficial for solid state lasers (especially Yb)

Higher efficiency and gain for Yb:YAG at 175K



Thermal lensing also strongly reduced

Ertel *et al.* Opt. Expr. 19(27) 2011

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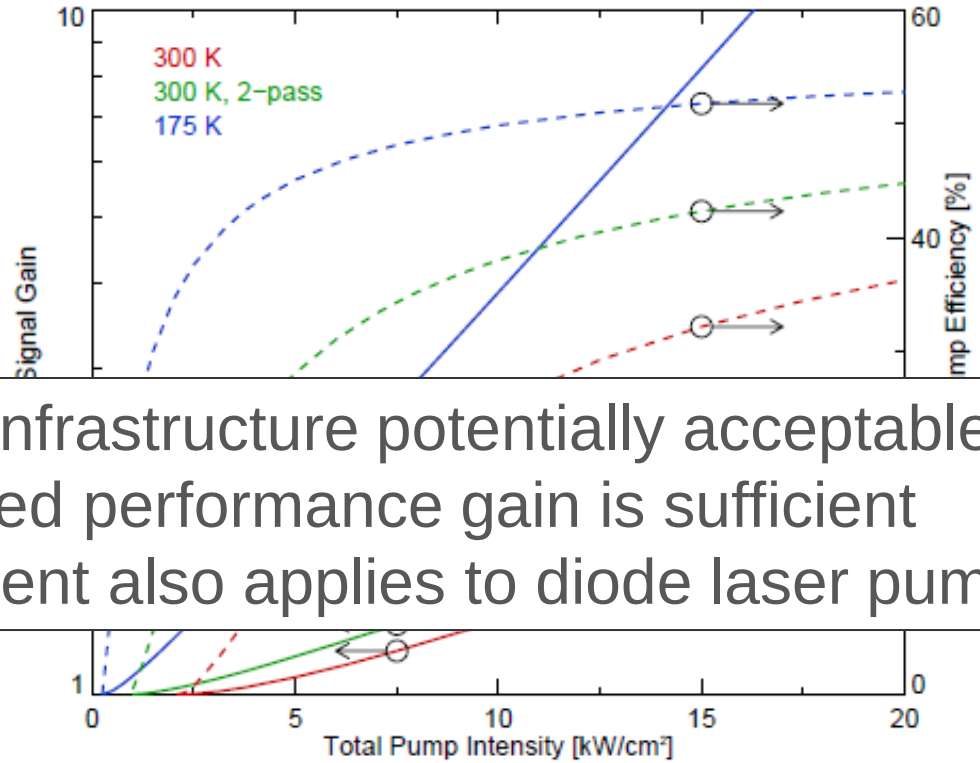


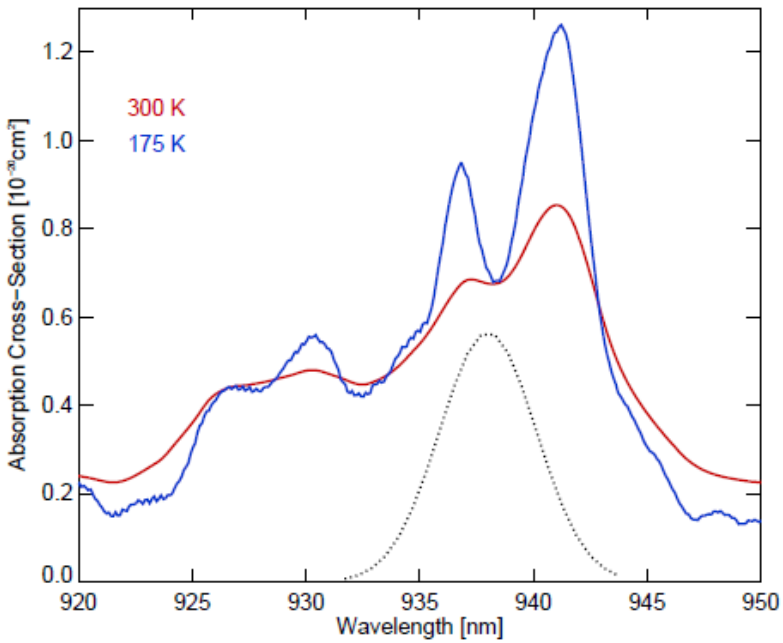
T < 0°C infrastructure potentially acceptable
... provided performance gain is sufficient
... argument also applies to diode laser pump sources

Thermal lensing also strongly reduced

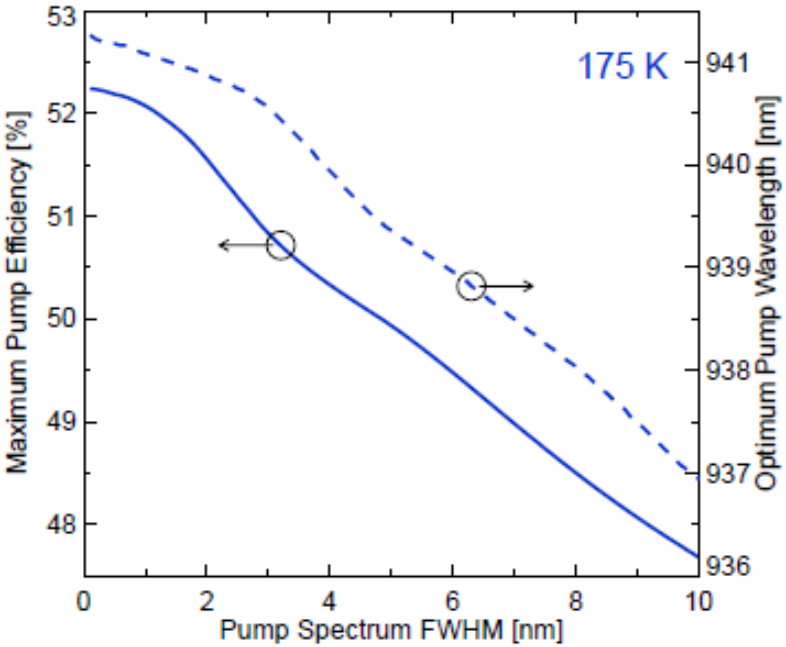
Ertel *et al.* Opt. Expr. 19(27) 2011

Narrow absorption, so narrow pump spectra needed

Absorption spectrum
Narrower at 175K



Pump lasers with small
spectral widths boost efficiency

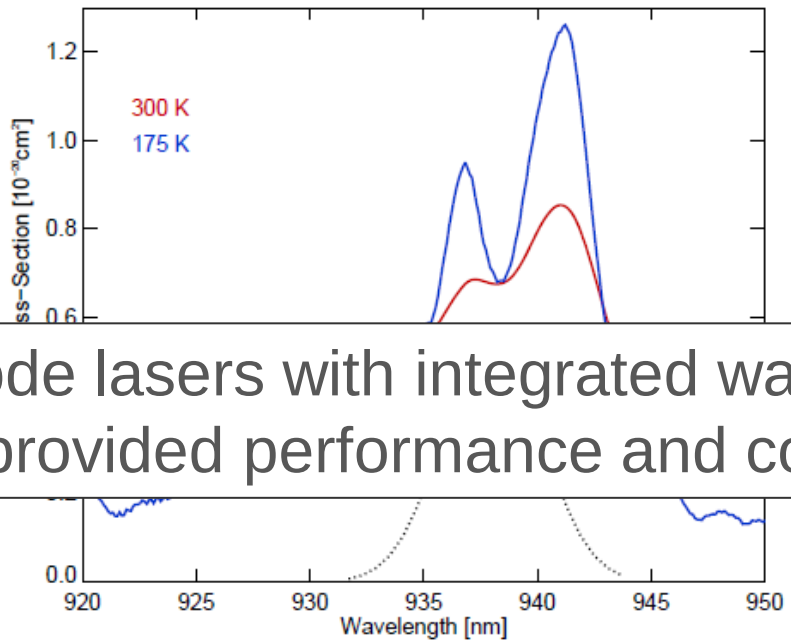


Also substantially easier (lower handling cost) In very large systems

Ertel *et al.* Opt. Expr. 19(27) 2011

Narrow absorption, so narrow pump spectra needed

Absorption spectrum
Narrower at 175K



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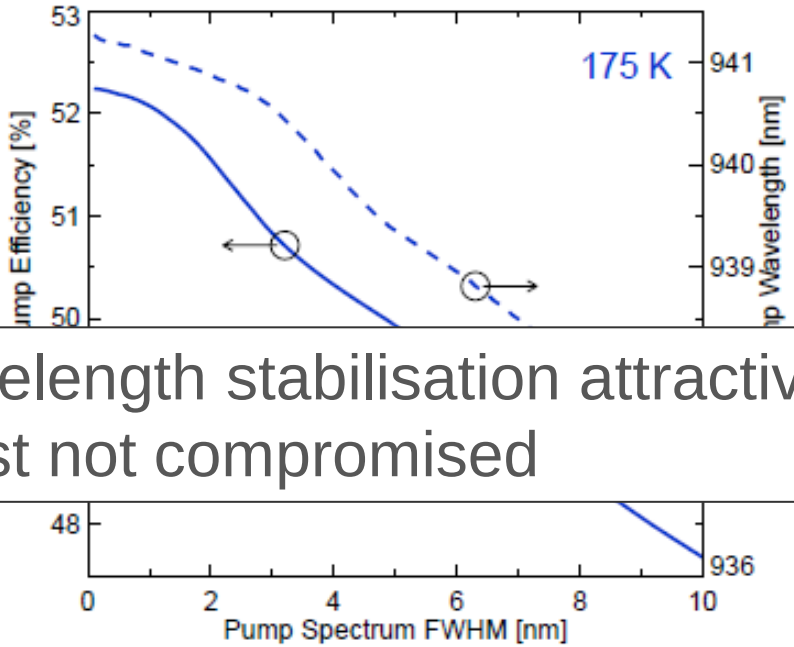

Diode lasers with integrated wavelength stabilisation attractive
... provided performance and cost not compromised

Also substantially easier (lower handling cost) In very large systems

Ertel *et al.* Opt. Expr. 19(27) 2011

Team

Leibniz Gemeinschaft

Funding via
SAW-Competition
Topic: „High risk“

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Research
Technology development
Prototype construction
(872nm and 940nm)

Lawrence Livermore National Laboratory

Assessment of prototypes
Confirm suitability for LIFE (Nd)

Science & Technology Facilities Council

Assessment of prototypes
Confirm suitability for HiPER (Yb)

Program start: Jan 2012

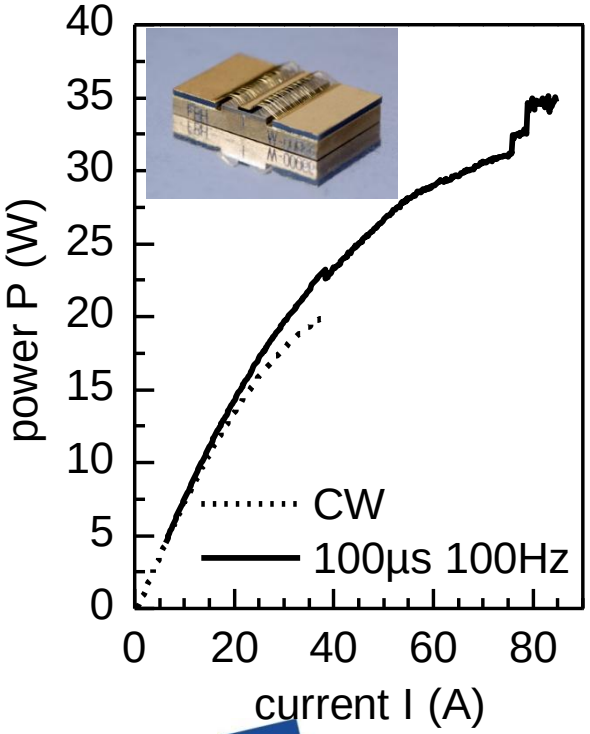
Contents

2kW QCW bars plausible - single emitter extrapolation

- State of the art diode laser technology enables very high peak powers
  - **High quality design and technology essential (low defect densities)**
  - **Laser facets with high damage thresholds are crucial (facet passivation) [1]**

- FBH 100µm stripe single emitters at 975nm demonstrate very high powers [2]:
  - **Peak CW power > 20W**
  - **Peak QCW power > 30W (100µs, 100Hz)**
  - **Reliable CW power to ~ 20W („proof of concept“)**

- Consistent with QCW power per bar > 1600 W
  - **Assuming 1-cm bars with > 80 single emitters**



[1] P. Ressel *et al.* IEEE Photon. Technol. Lett **17**(5) pp. 962-964 (2005)
[2] P Crump *et al.* Proc. SPIE 8241, 82410U (2012).

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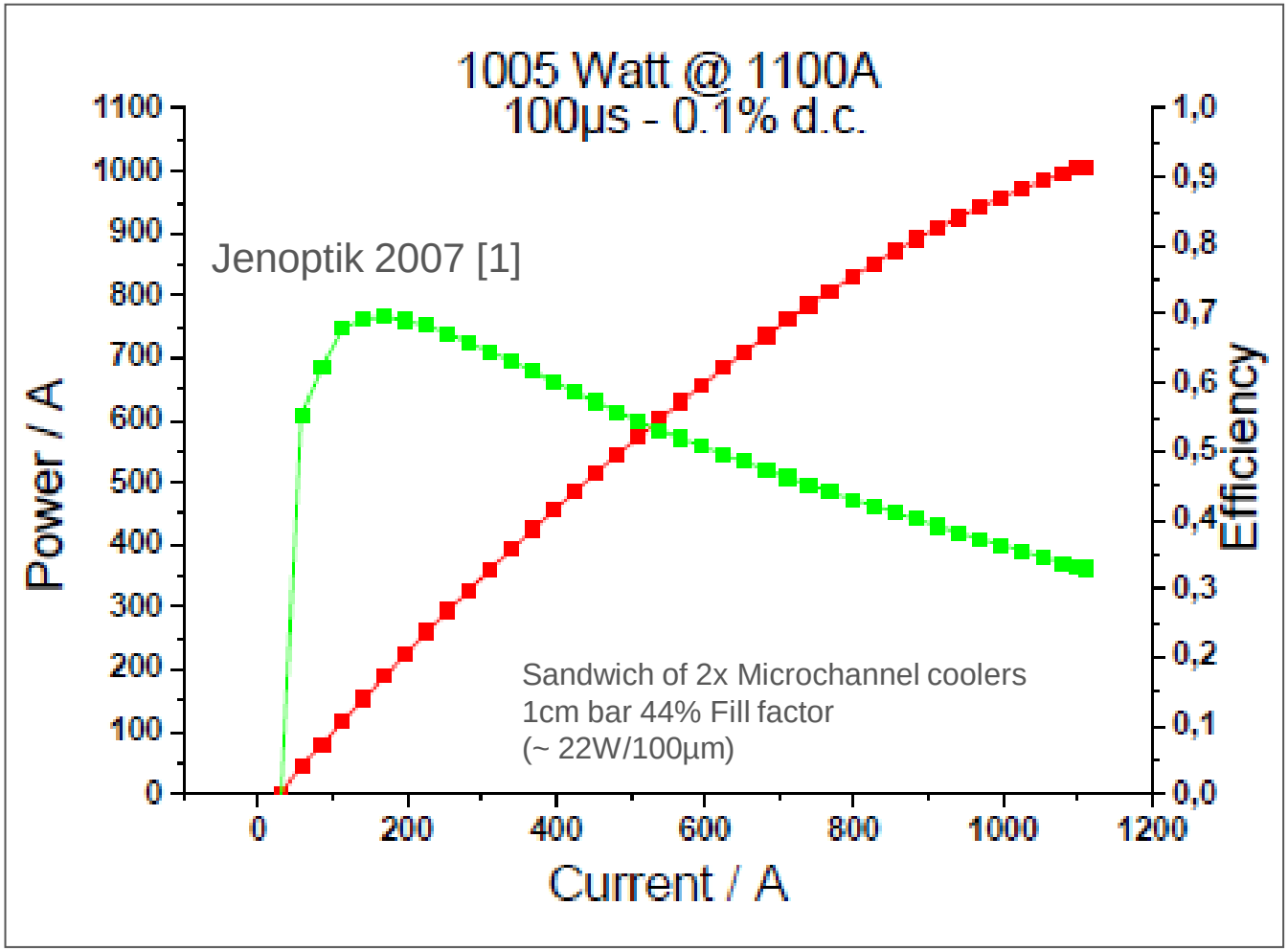
1kW QCW bars demonstrated in lab since 2007



[1] D. Schröder et al. Proc. SPIE 6456, 64560N (2007).

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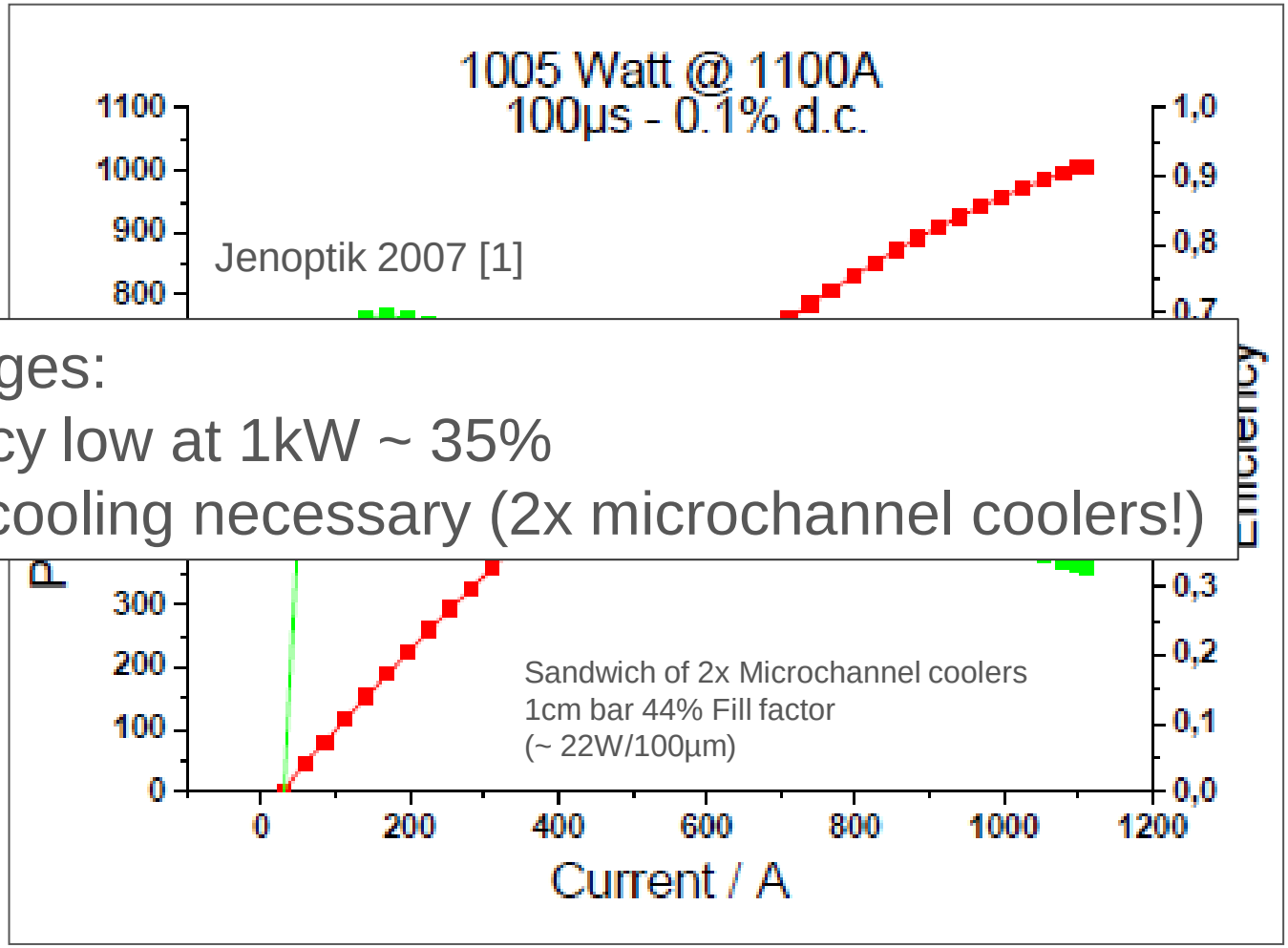
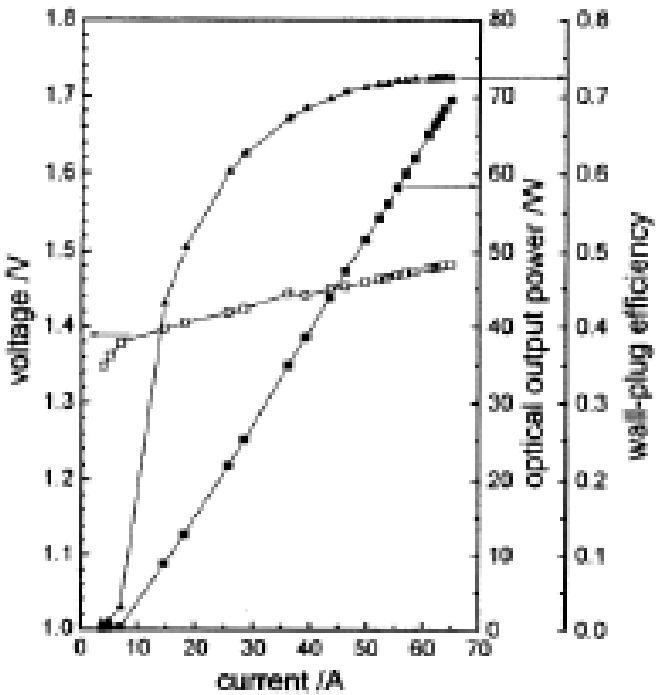


Challenges:
Efficiency low at 1kW ~ 35%
Strong cooling necessary (2x microchannel coolers!)

[1] D. Schröder et al. Proc. SPIE 6456, 64560N (2007).

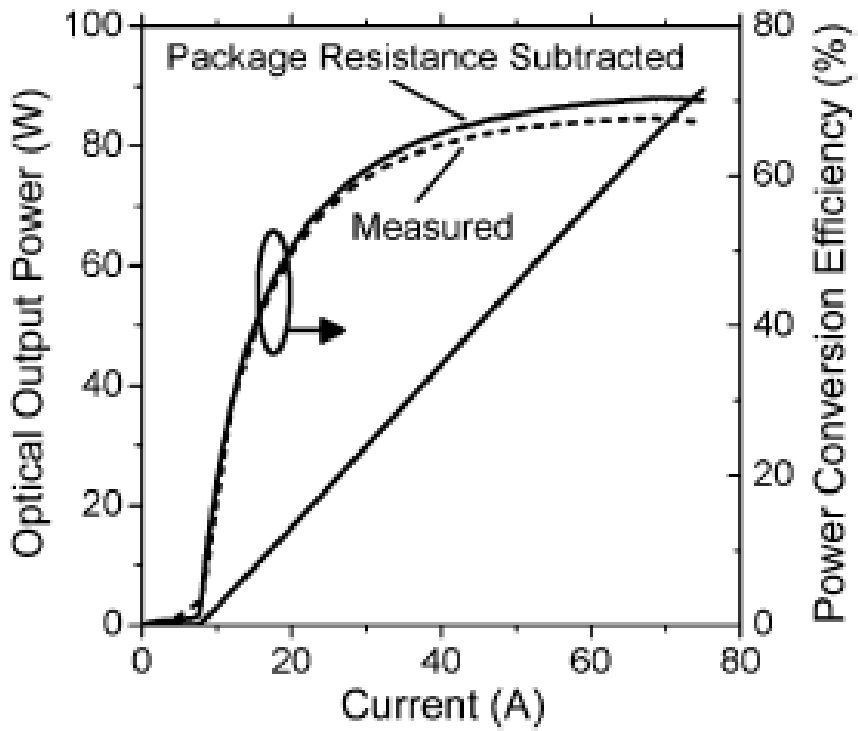
25°C Bars with η_E > 70% obtained in lab since mid 2000

FBH Bars η_E > 70% at 940nm [1]



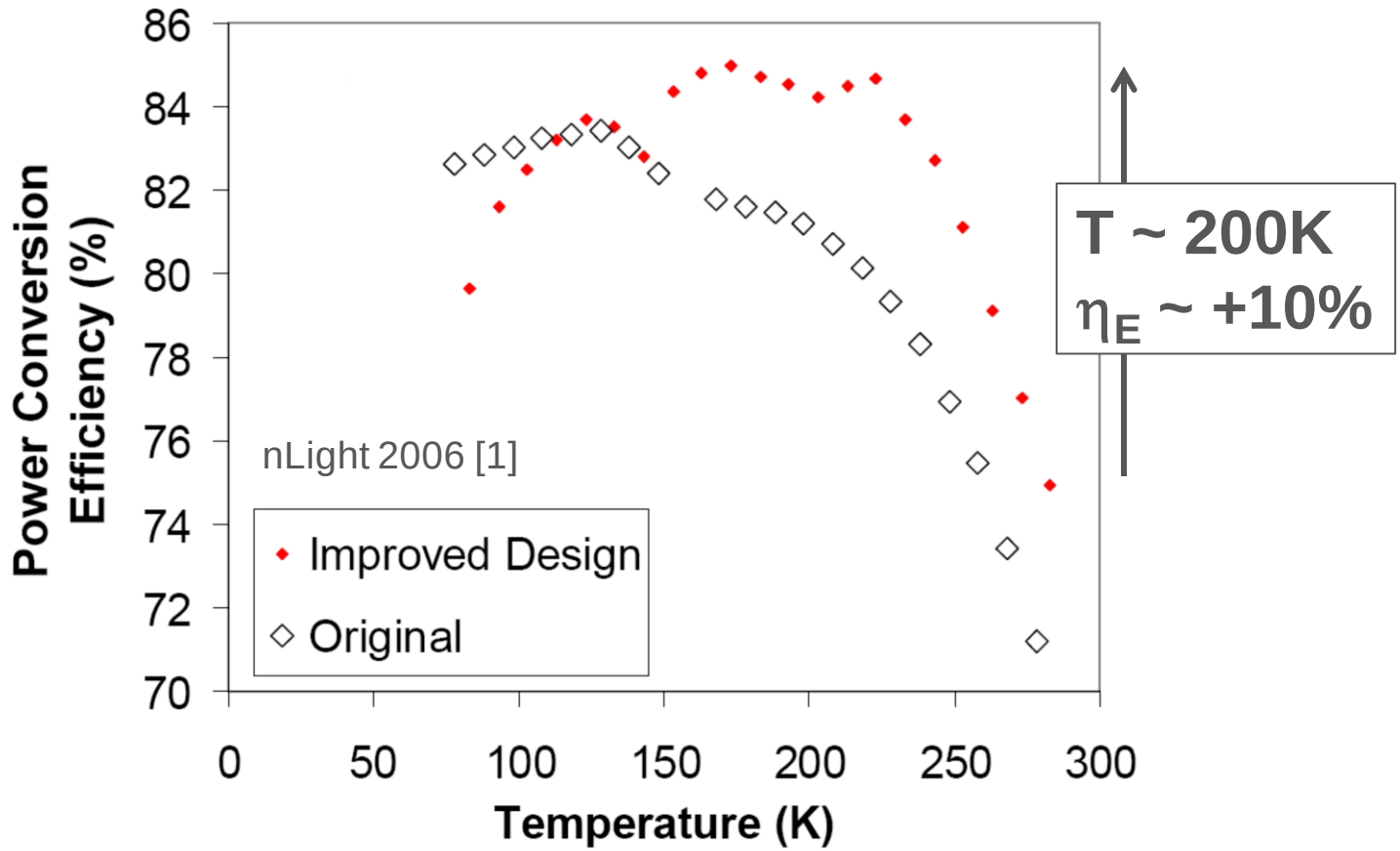
[1] A Knigge *et al.* Electron, Lett. 41 pp250-251 (2005)

FBH Bars η_E > 70% at 808nm [2]



[2] P Crump *et al.* IEEE PTL 20(16) pp1378-1380 (2008)

Efficiency > 80% plausible – single emitter demonstration



[1] P. Crump *et al.* Proc. CLEO/QELS, Baltimore USA, p. 1 (2006)

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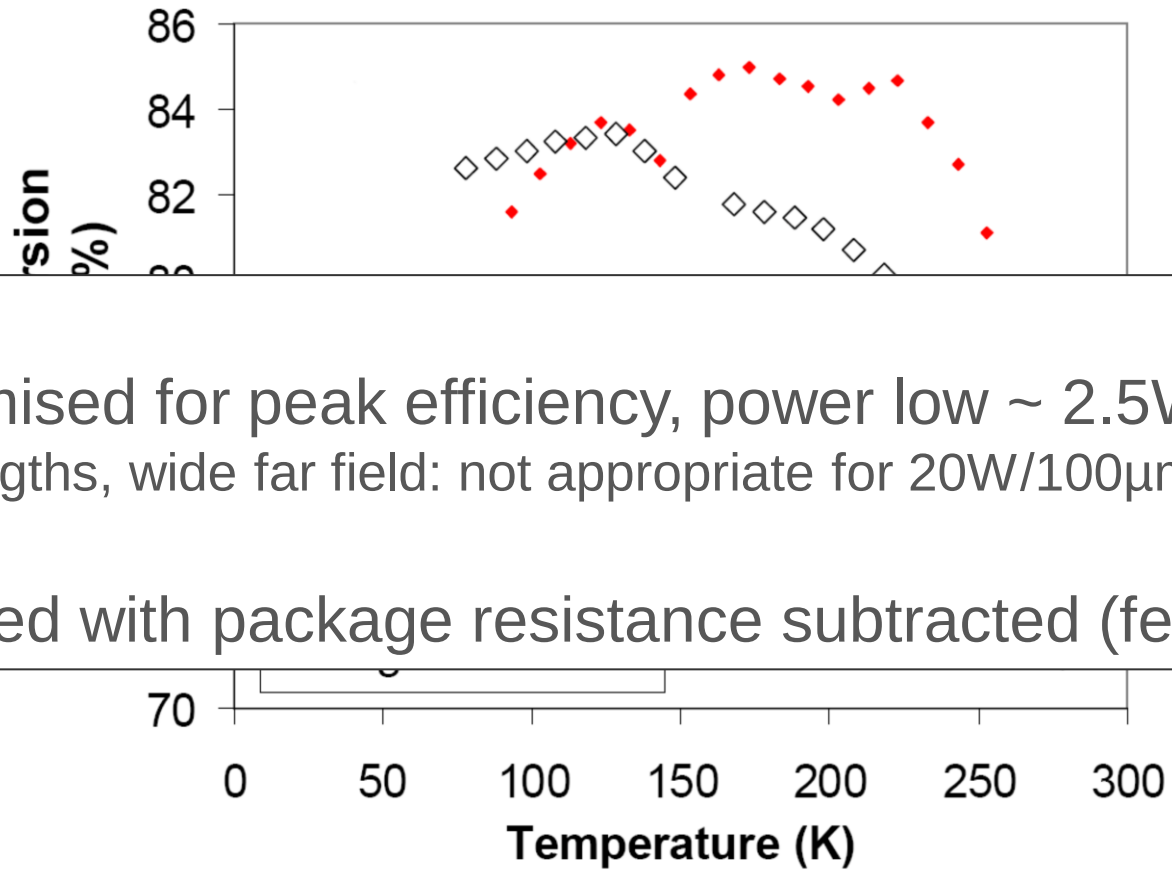


Challenges:

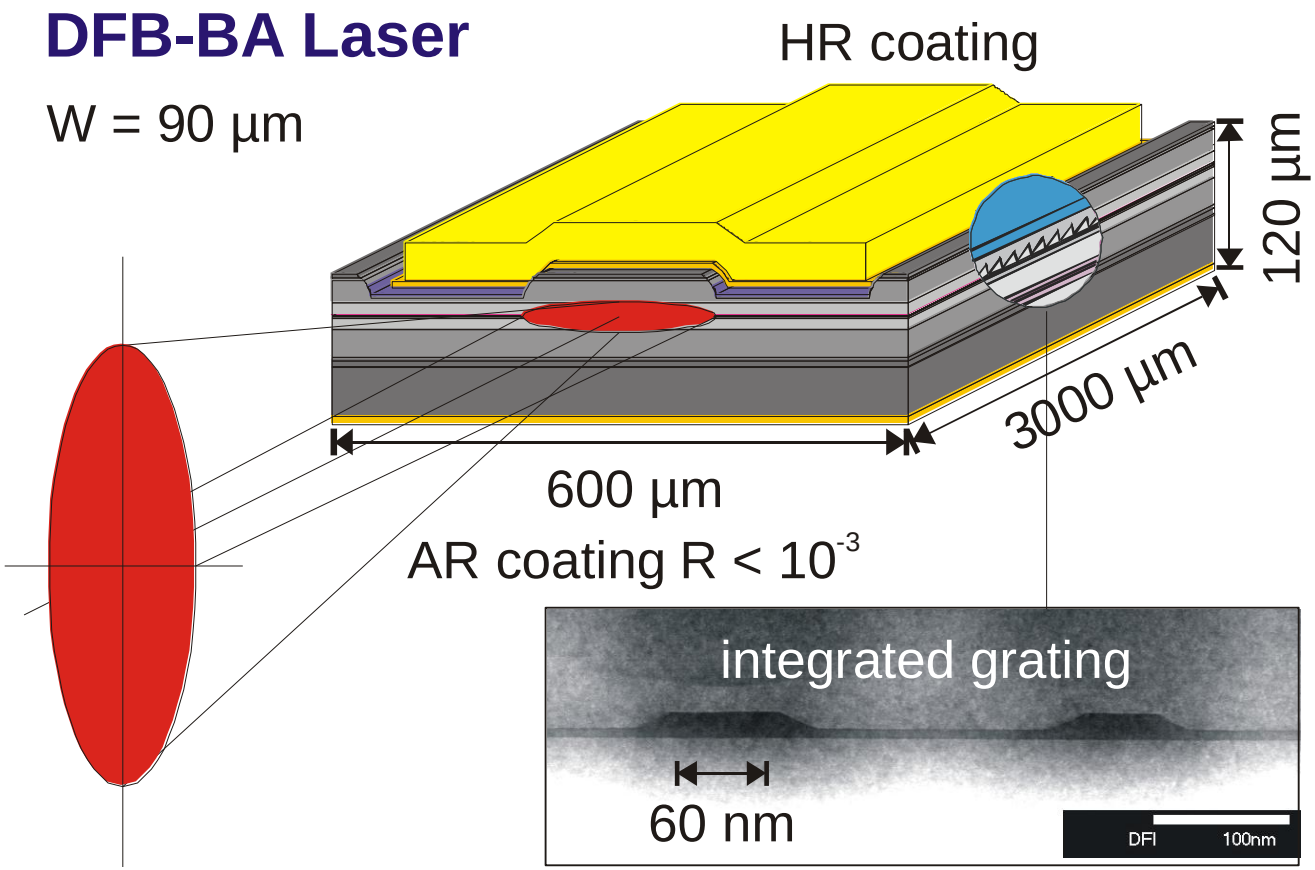
Heavily optimised for peak efficiency, power low ~ 2.5W/100µm

Short cavity lengths, wide far field: not appropriate for 20W/100µm!

Results quoted with package resistance subtracted (few %)

[1] P. Crump *et al.* Proc. CLEO/QELS, Baltimore USA, p. 1 (2006)

FBH Technology: Low loss gratings inside the diode laser



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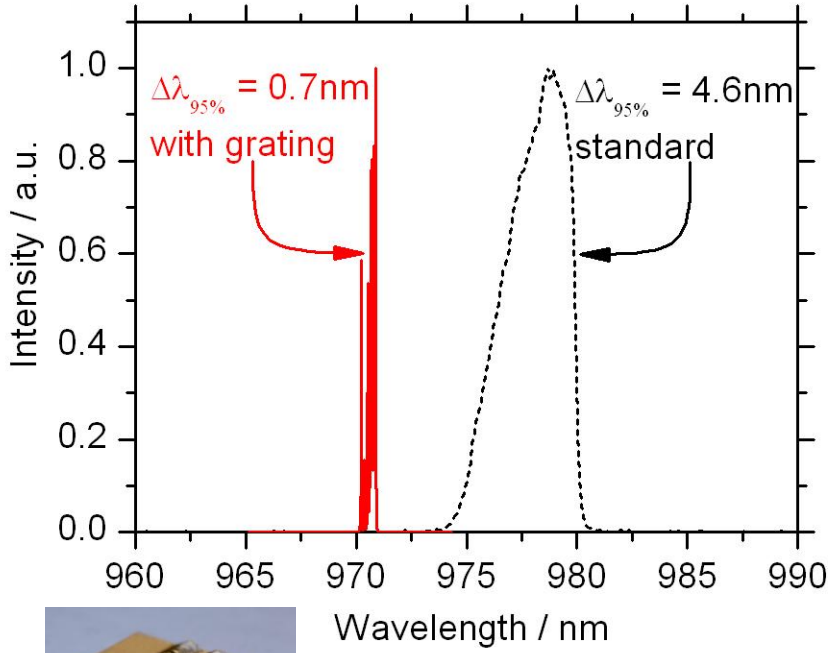
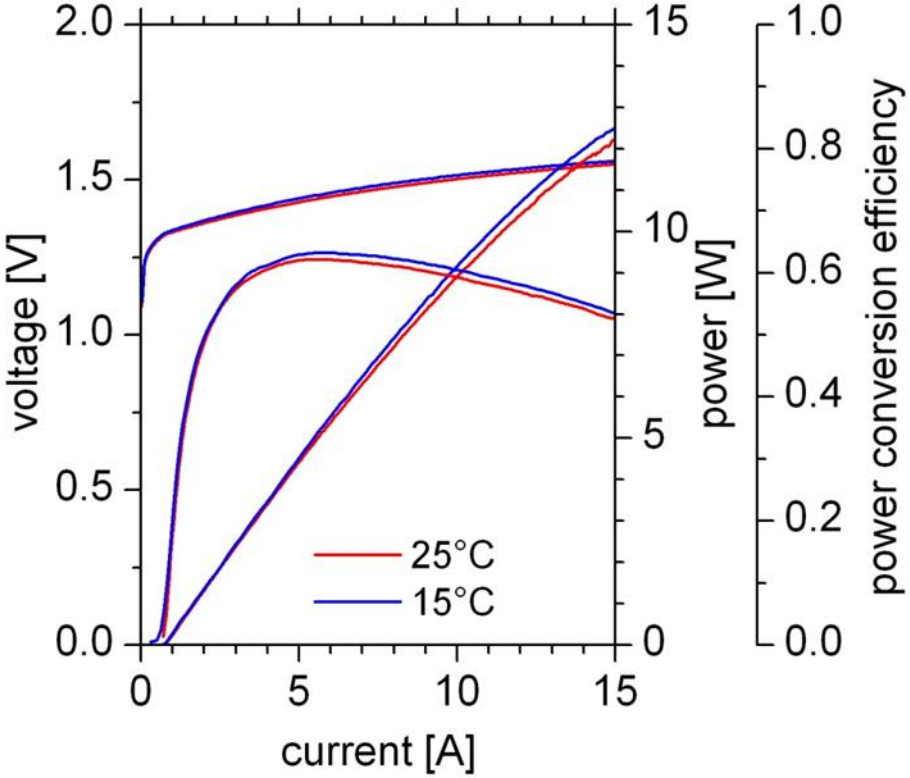
High power and efficiency demonstrated in DFB-BA at FBH

Spectrum narrowed < 1nm



Conversion efficiency η_E > 60%
< 5% reduced c.f. reference devices



Schultz *et al.*, Appl. Phys. Lett. **100**, 201115 (2012)

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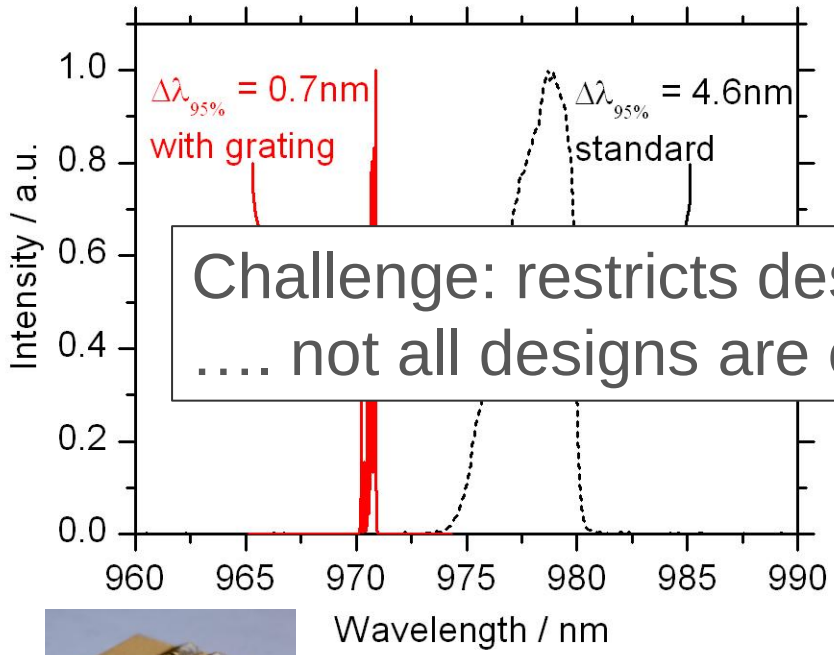
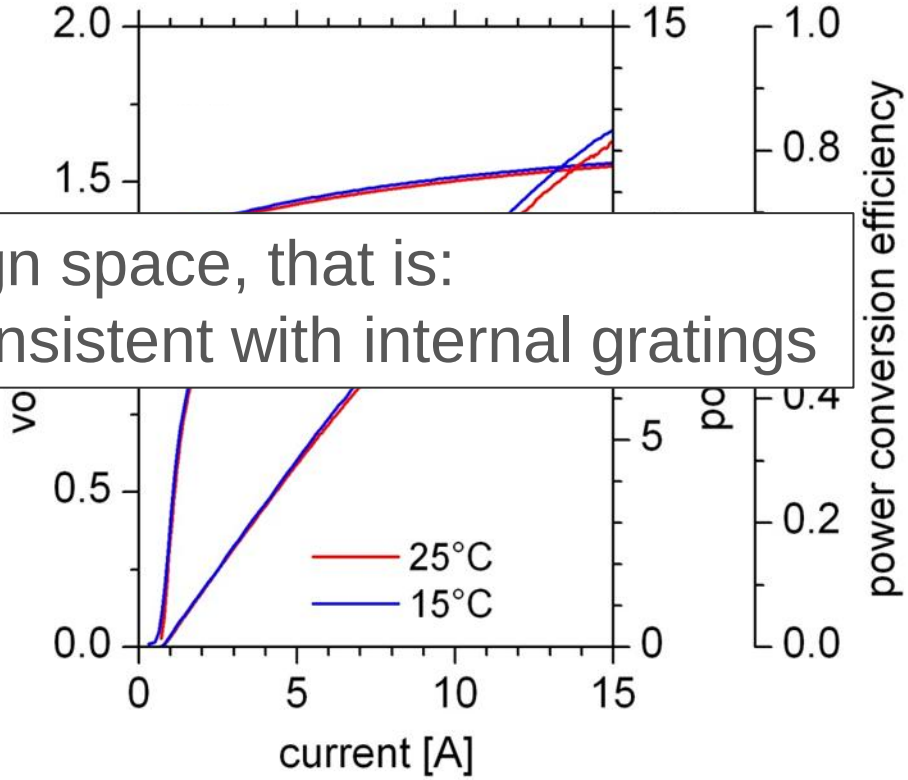




Challenge: restricts design space, that is:
…. not all designs are consistent with internal gratings

Schultz *et al.*, Appl. Phys. Lett. **100**, 201115 (2012)

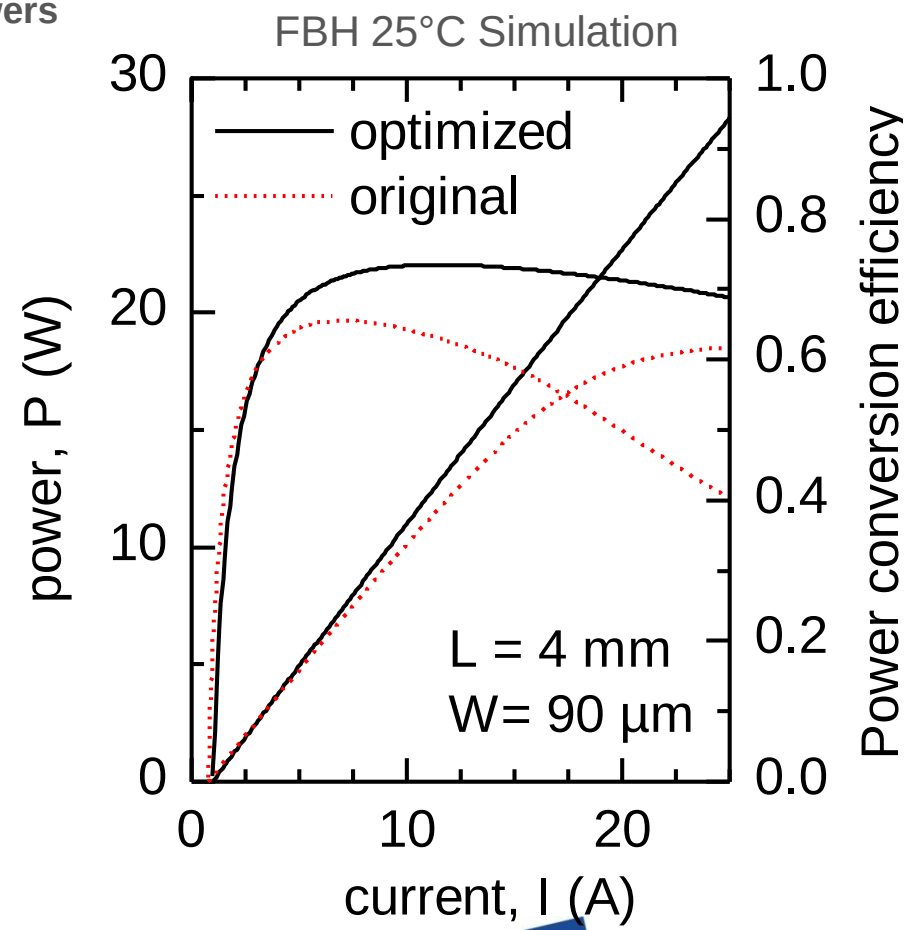
Contents

Work Package 1: Device design for efficiency and power

- Design challenges
  - **Understand, leverage material changes at 200K**
  - **High efficiency, sustained to high powers**
  - **Compatible with internal gratings**
  - **Compatible with long life time**

- Novel laser designs in development
  - **Promising initial results (no DFB)**
  - **Optimization to follow**

- Design goals: use 200K to enable
  - **η_E(Peak) ~ 90%**
  - **η_E(20W/100µm) ~ 85%**
  - **η_E(DFB) > 80%**



[1] P Crump et al. Proc. SPIE 8241, 82410U (2012).

Work Package 2: Manufacturing of prototypes

- Combine efficient designs with grating technology, wavelength targeting for 200K
- Construct high-fill factor laser bars, as well as single emitters
- Passivate facets (very high damage threshold)
- Package
- Deliver for assessment

First devices completed August 2012

Work Package 3: Characterisation

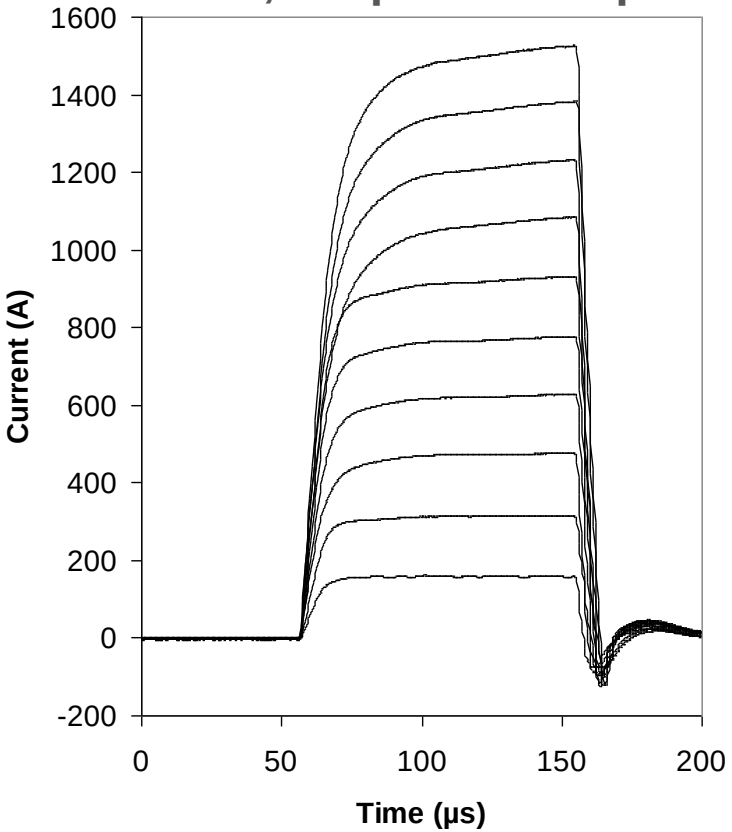
- Development of custom current supply (subcontract Amtron GmbH, Germany)
  - **Current:** **0 - 2000A**
  - **Pulse width:** **100µs - 2ms**
  - **Repetition rate:** **10 - 20Hz**

- Construction of custom test station
  - **Passive cooling (circulating fluid)**
  - **T: 200-300K**
  - **Current status: T > 220K (-50°C)**
  - **Controlled environment**

- It. 1 Characterization of prototypes
  - **„Time= 0“ Benchmarking**
  - **calibration of design**

- First testing started September 2012

0 - 1.5kA, 100µs current pulses

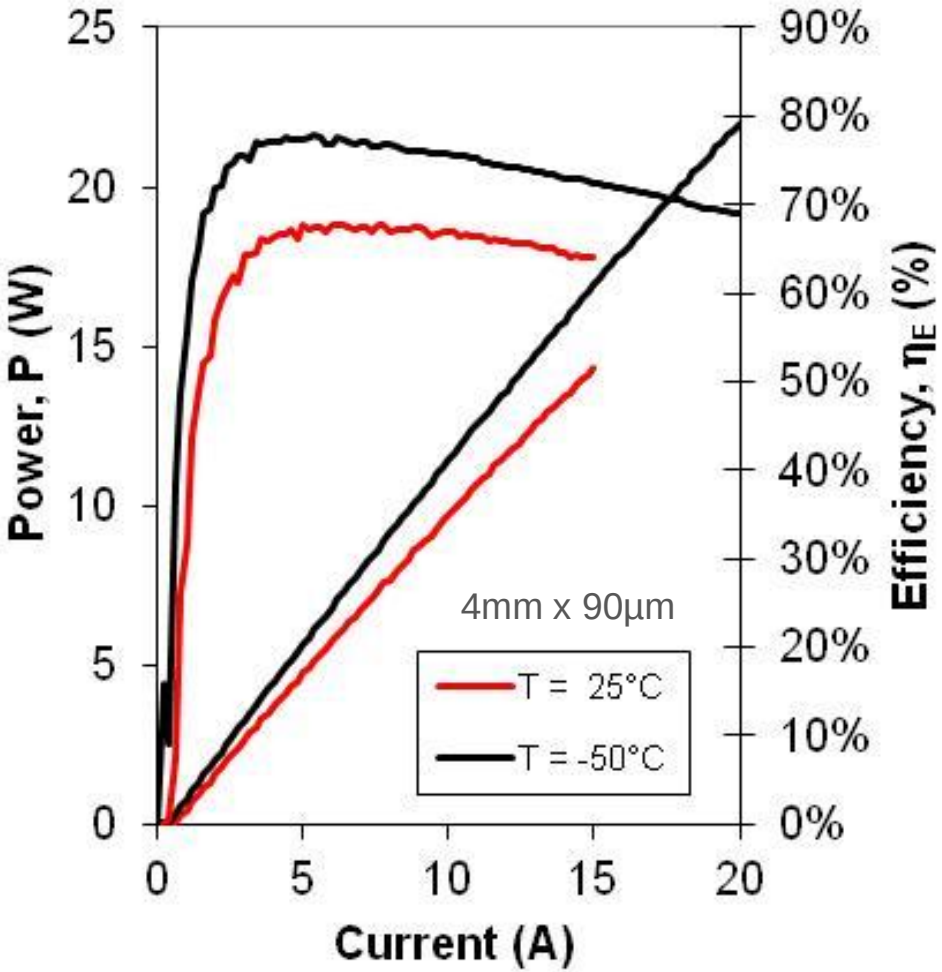


AMTRON = FBH Leibniz Ferdinand-Braun-Institut

Contents

Initial test of 940-nm FBH baseline single emitters to -50°C

- Date shown for 940nm single emitter
  - **Stripe width here is 90µm**
  - **Bars contain ~ 80x such lasers**
  - **QCW test = 400µs 10Hz**
  - **η_E (Peak, 25°C) = 68%**
- Efficiency ~ 10% improved at -50°C
  - **η_E (Peak) = 78%**
- Power scaling at -50°C:
  - **10W/100µm ~ 800W bar, η_E = 77%**
  - **20W/100µm ~ 1.6kW bar, η_E = 72%**



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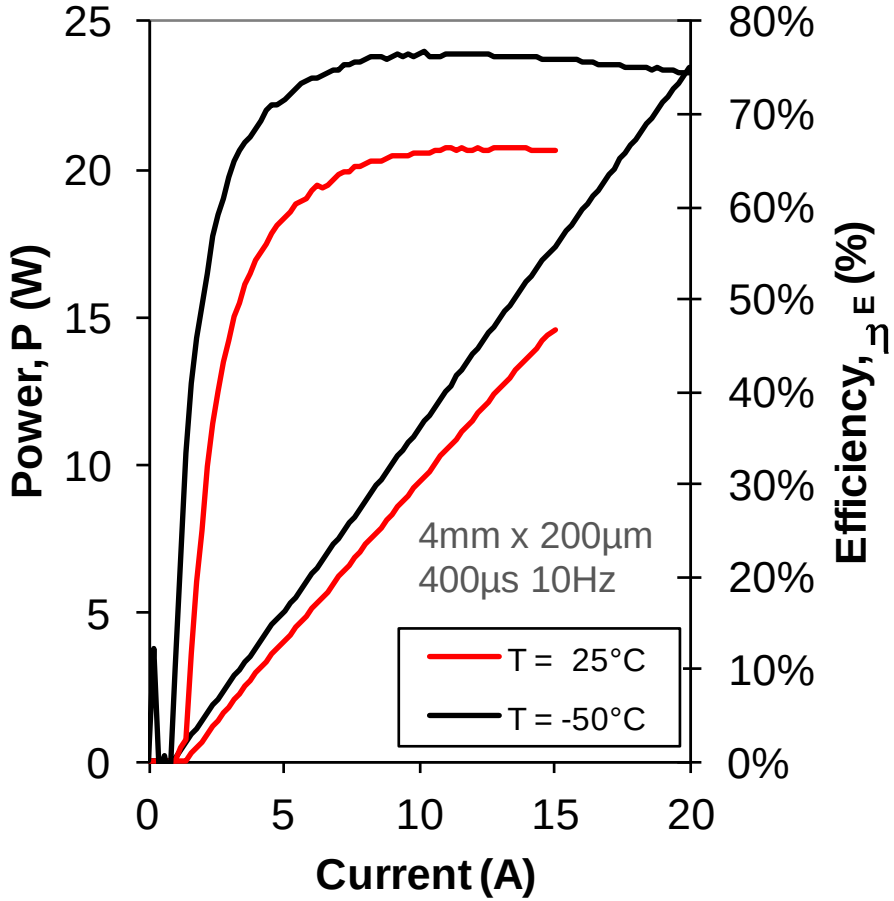
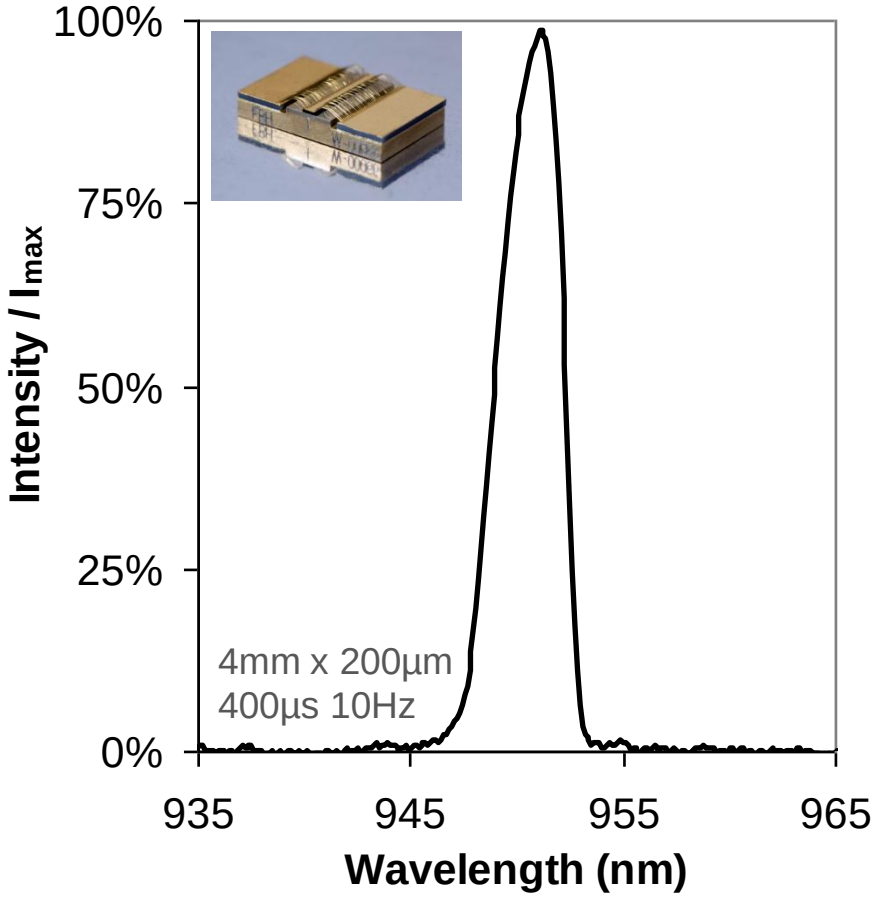
Initial test of 9xx-nm single emitters at T = -50°C

Design target: 940nm at 200K





η_E (Peak) = 77% at -50°C

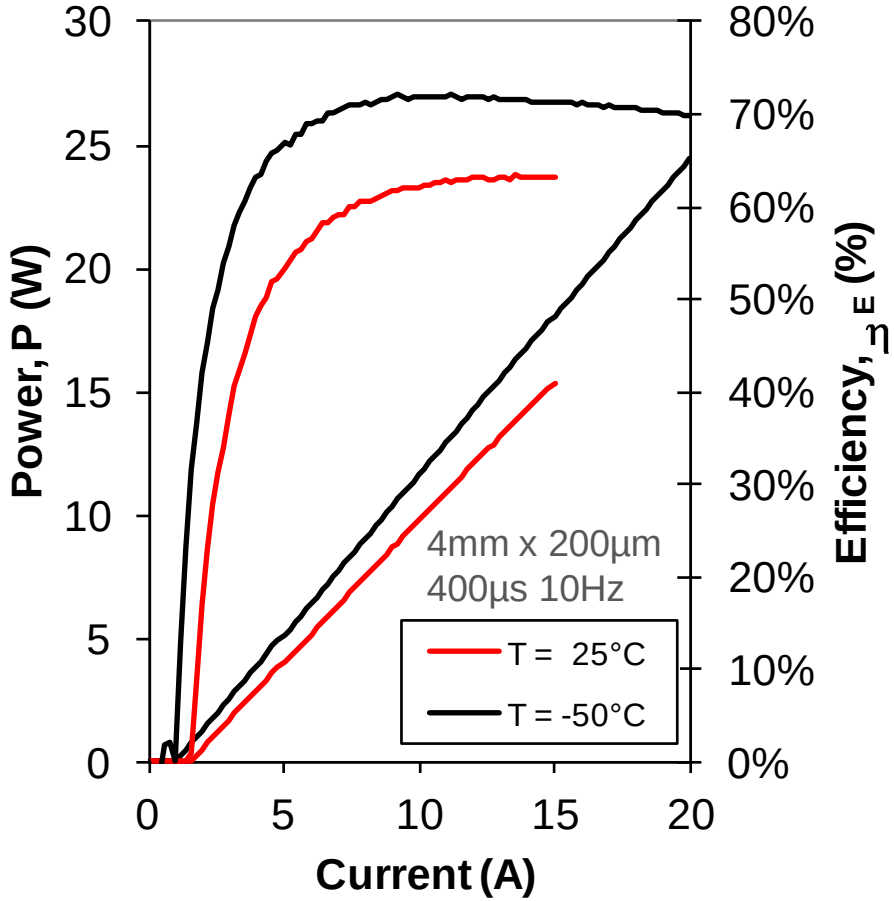
η_E (10W/100µm) = 75%

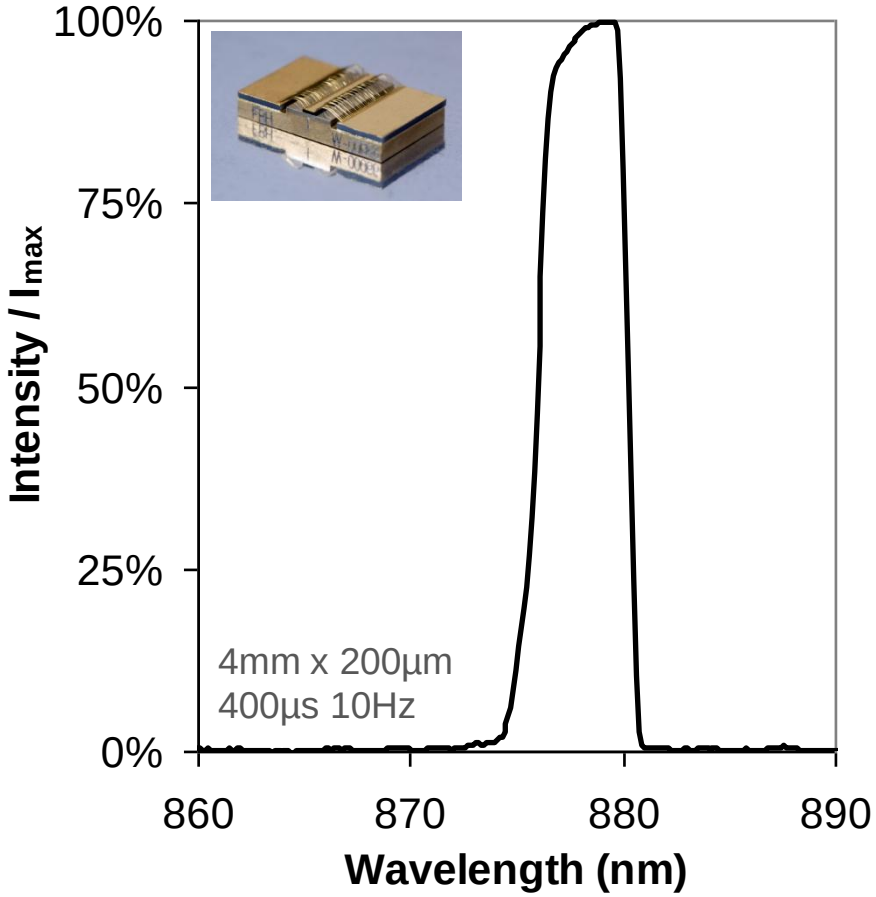
$\lambda_{50\%}$ = 950.6 nm (6nm)

$\Delta\lambda_{95\%}$ = 4.8 nm

Initial test of 88x-nm single emitters at T = -50°C

Design target: 872nm at 200K





η_E (Peak) = 73% at -50°C

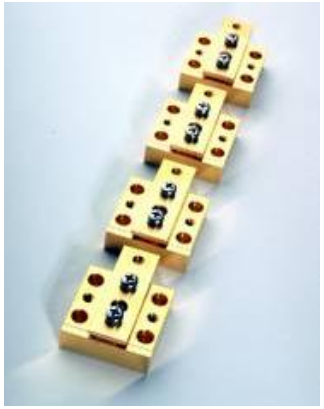
η_E (10W/100µm) = 71%

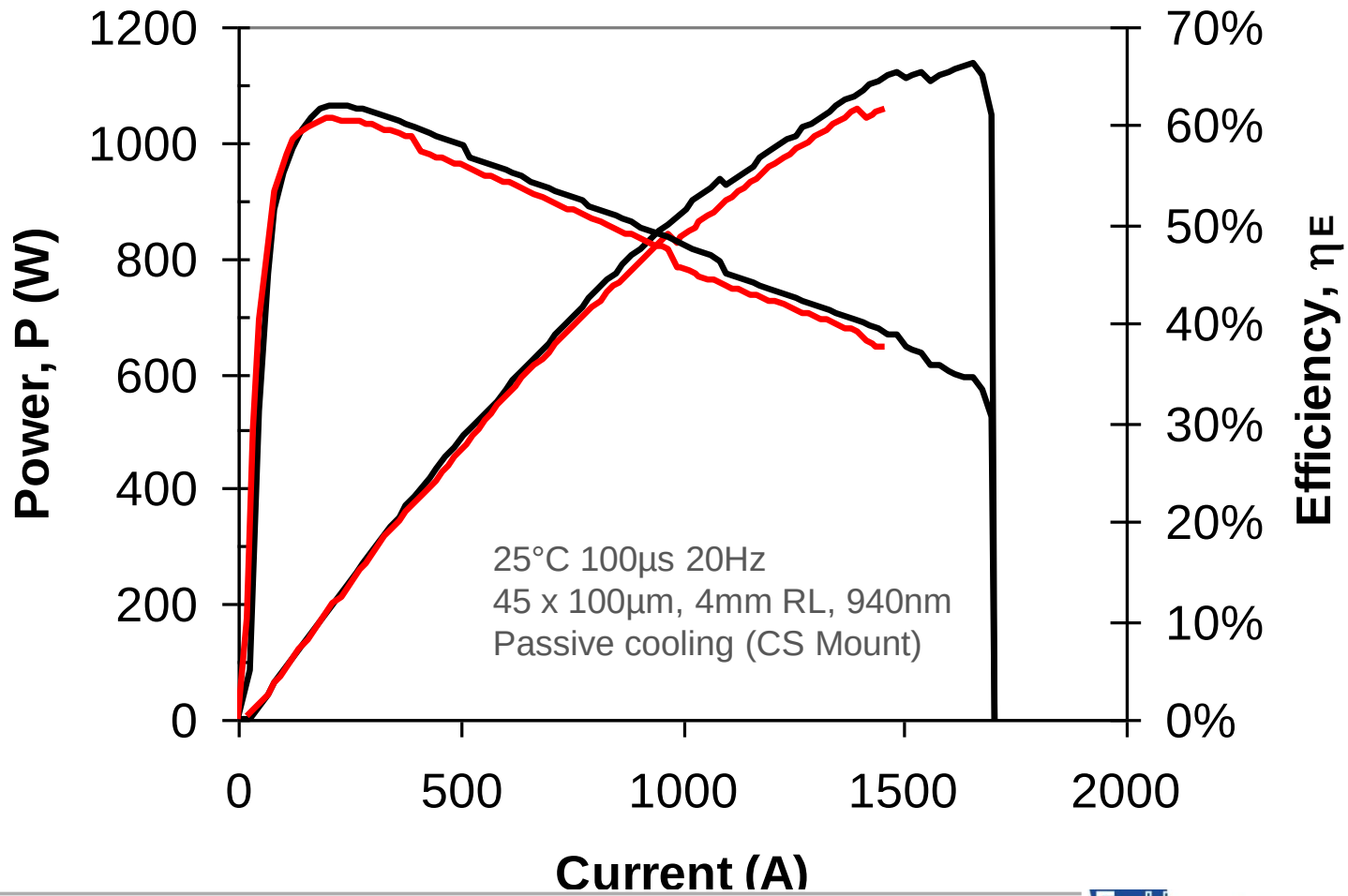
$\lambda_{50\%}$ = 878 nm (6nm)

$\Delta\lambda_{95\%}$ = 5.0 nm

Initial 25°C Test of FBH "Baseline" Bars: η_E(1kW) = 43%

Long cavity and higher efficiency enable > 1kW passively cooled
Next: better design, increased fill factor, lower temperatures





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Contents

Conclusions

- HEC-DPSSL systems require higher performance diode laser pumps
  - **LIF-based systems for power generation have the most stringent requirements**

- Project „Cryolaser“ targets the required step-improvement in performance
  - **Performance improvement to be enabled by customized design for T < 0°C**
  - **Would make use of T < 0°C architecture in discussion for solid state crystals**

- Technical goals: QCW diode laser pump bars at 872nm and 940nm
  - **Strategy: High-risk, high-impact development, targeting performance breakthough**
    - **Power per bar > 1.6kW at a conversion efficiency of> 80%**
    - **Spectral width < 1 nm (95% power content)**

- Program goals are a plausible extrapolation of current diode laser results
  - **Performance to be confirmed by testing at LLNL, STFC**

- Initial FBH prototype testing started
  - **Bars with 45% fill factor:** P_{max} **> 1kW at 25°C**
  - **Single emitters at -50°C:** η_E **> 70% at 10-20W per 100µm (> 1.5 kW/ bar)**

- Much to be done!

Thank you for your attention!

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