Pump Diode Lasers: Applications and Technology

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Pump Diode Lasers

1. Photonic Market
   - Global Photonic Market
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   - Photonic Manufacturing

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   - Power Photonics

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   - Optical coupling to fiber
   - Heat removal

5. Status, Trends, Opportunities
   - VCSEL

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Based on Seminar by Berthold Schmidt: "High Power Laser Diodes: Technology and Applications" applications of High Power Semiconductor Lasers, San Diego, California, Oct 6, 2008

Reference: Optical Fiber Telecommunications, Academic Press, A: Components and Subsystems ISBN: 978-0-12-374171-4, chapter 5 "Pump Diode Lasers" by Ch. Harder

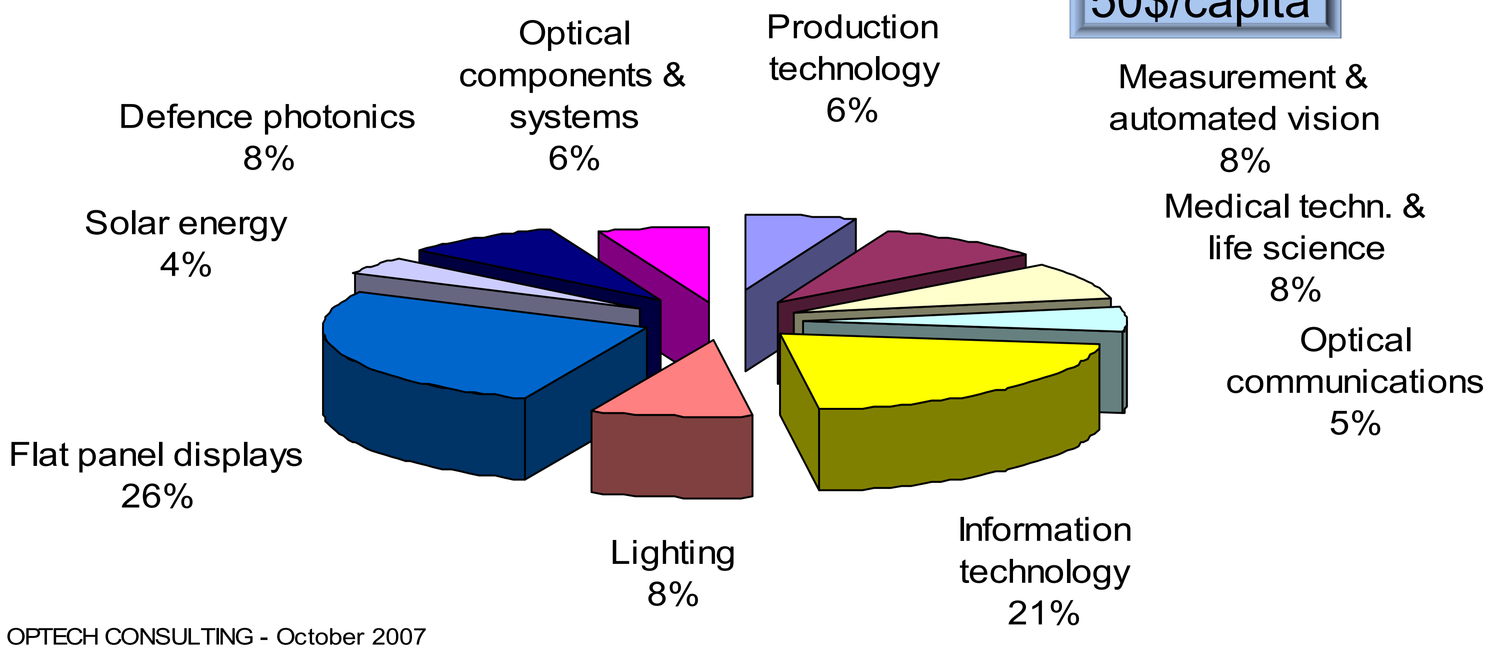
Global Photonic Market

Opportunities – The Market
World Market 2005 (production)

Photonics World Market by Sector, 2005

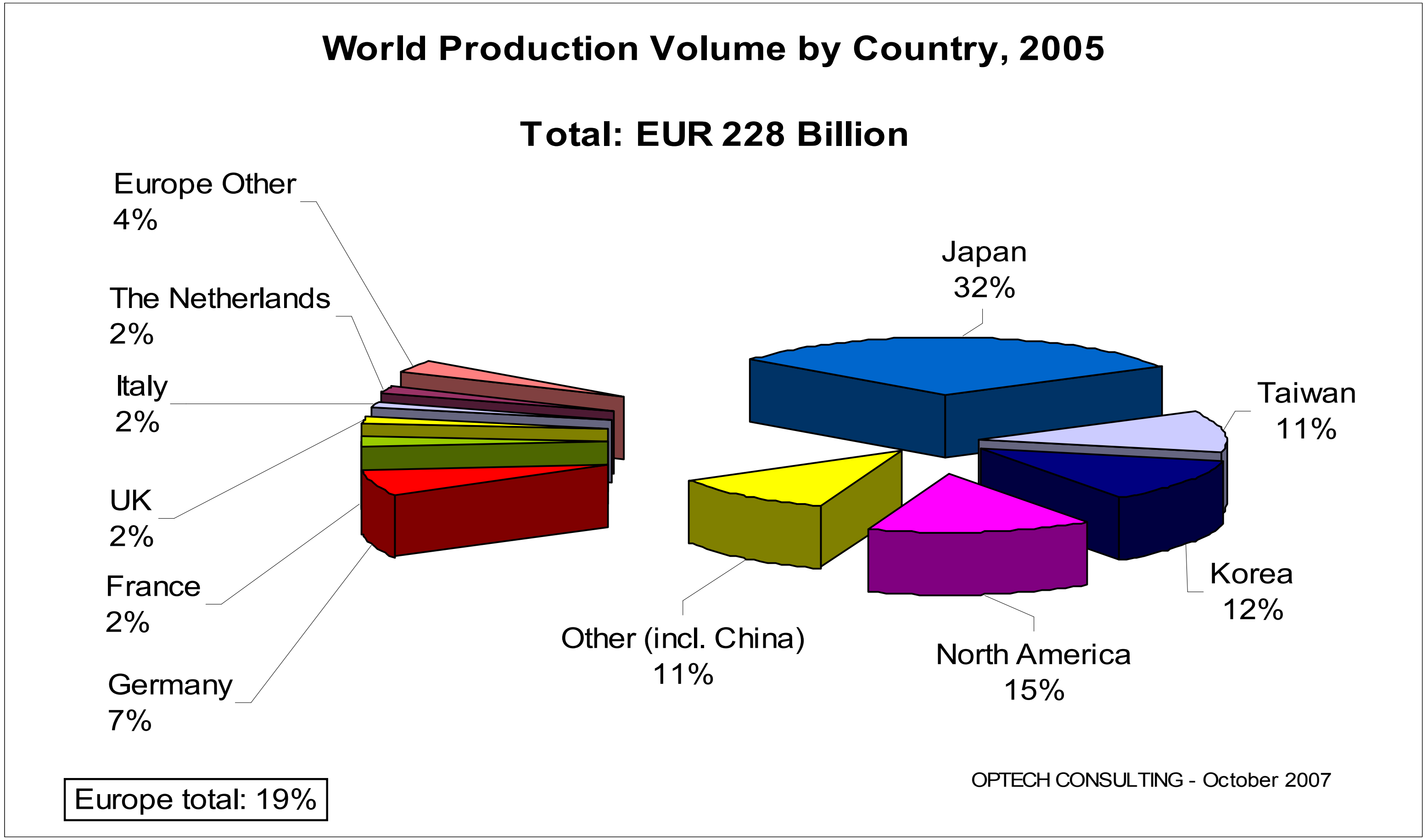
Total: EUR 228 Billion

Per Year
50$/capita

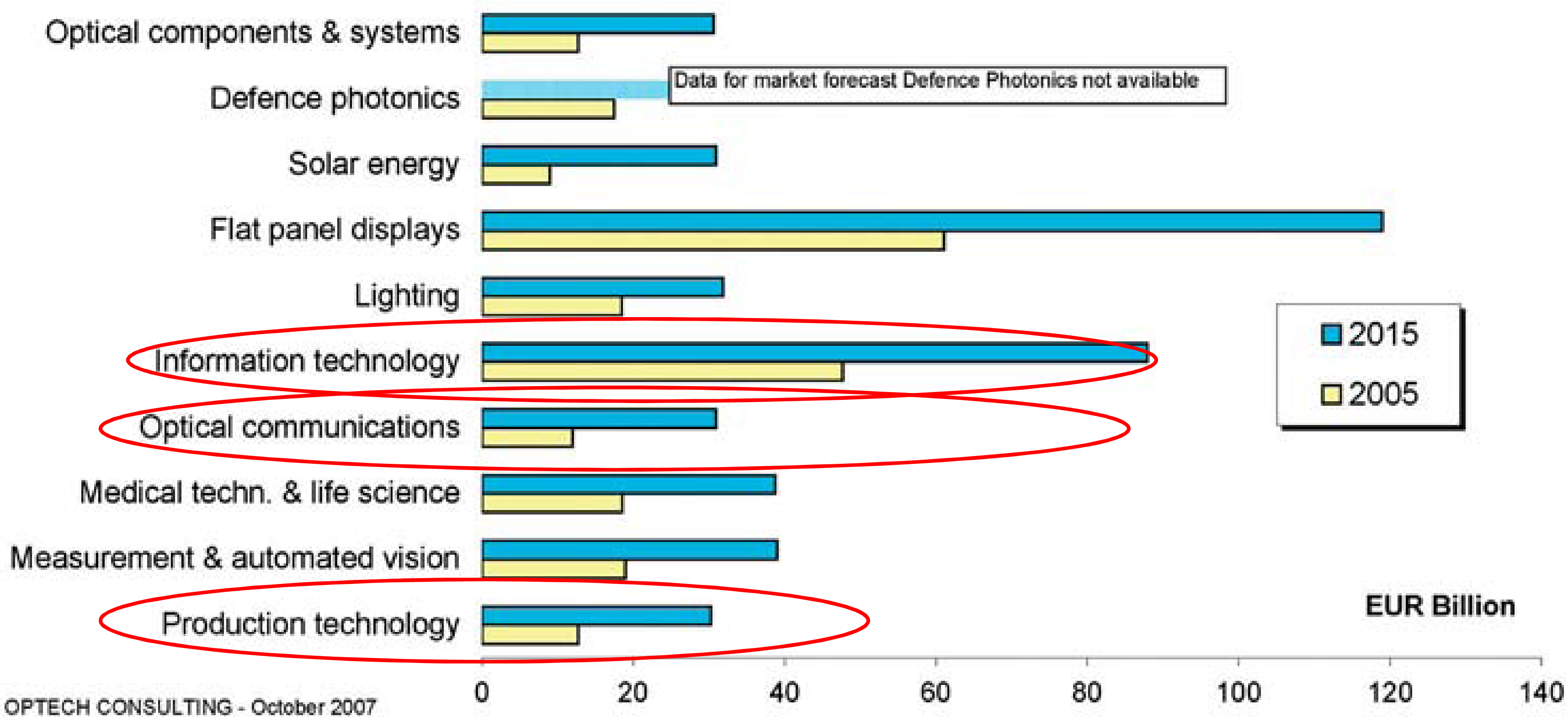


OPTECH CONSULTING - October 2007

Opportunities – The Market
World Production by country



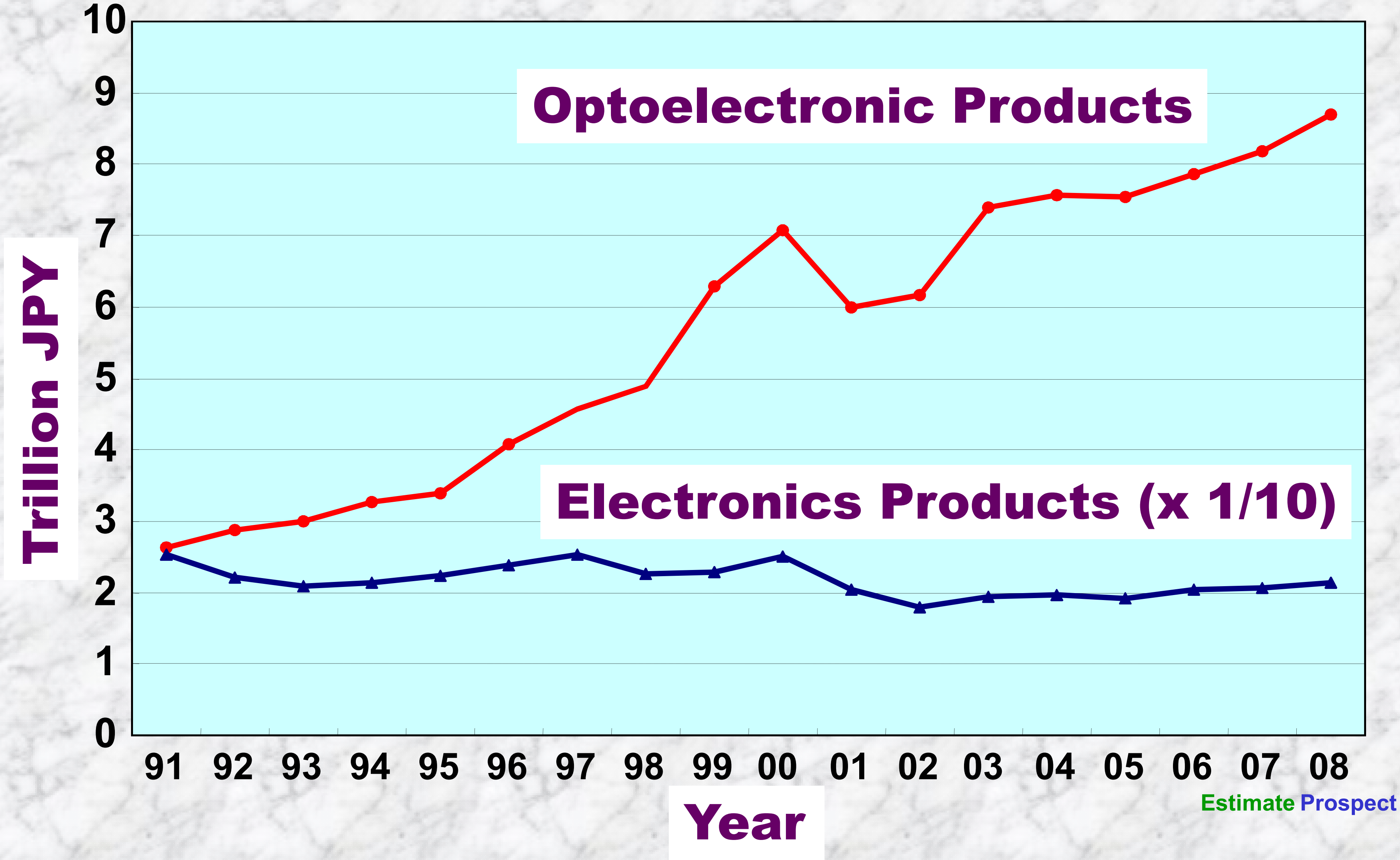
Projected Market Growth till 2015



- **Laser diode market in the range of only 1-2% of the overall photonics market**
- **Biggest Diode Share: Telecom, optical storage (75-90%)**
- **Gray areas: Value of material processing (system level), defense budget**

Global Photonic Market: Japan

Domestic Production - OE vs. Electronics



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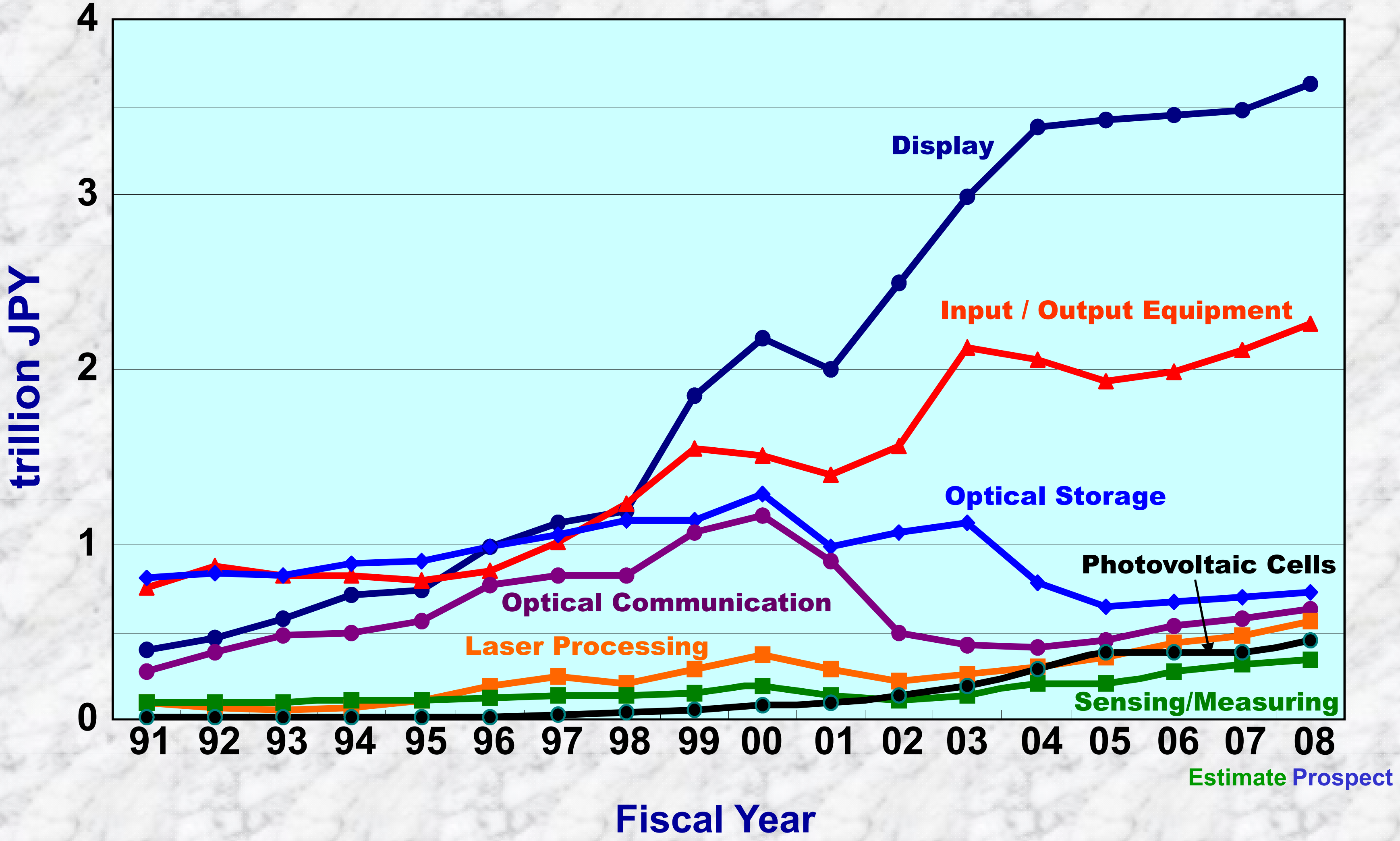
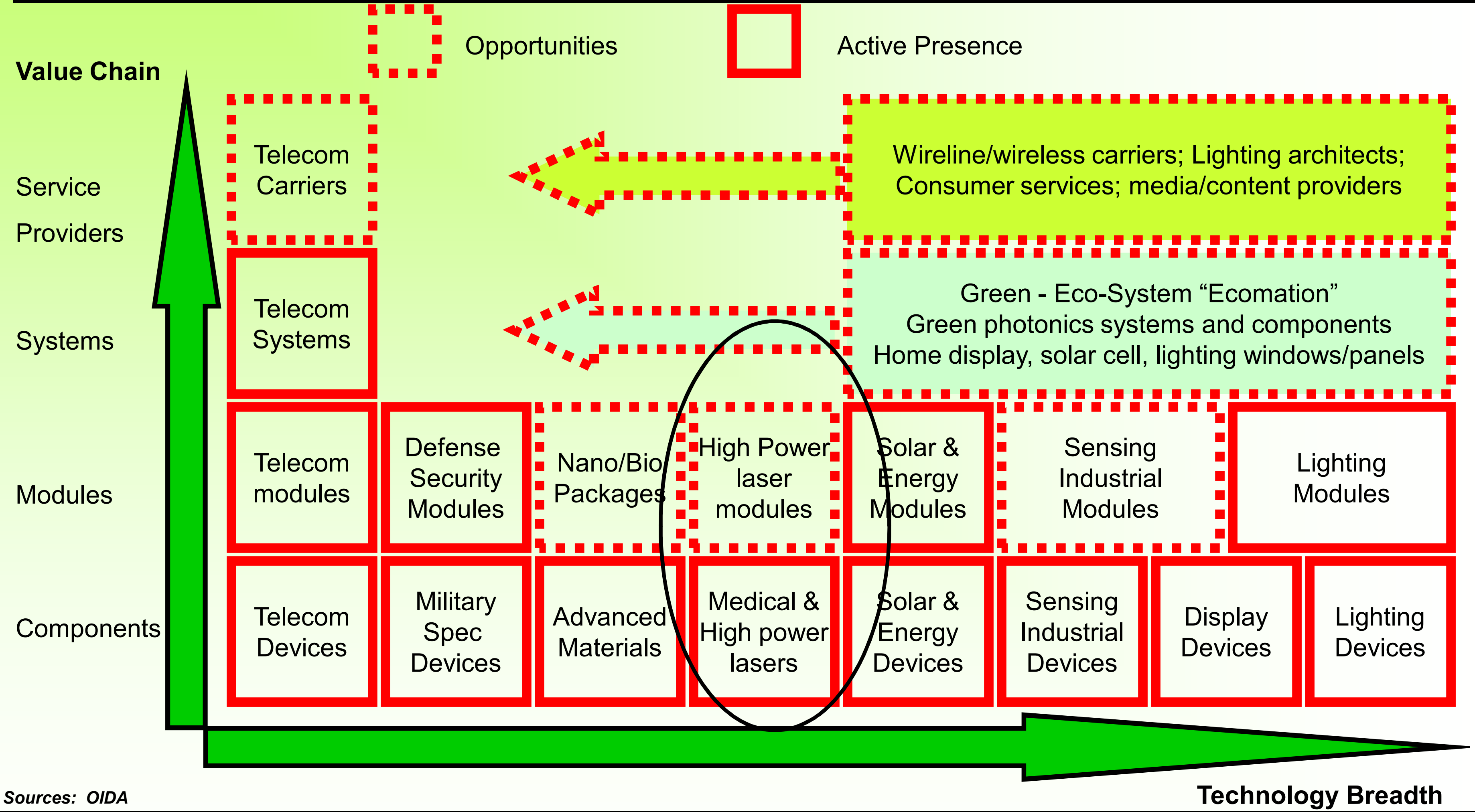
Domestic OE Products Trends by Field



Global Photonic Market: USA

OIDA is broadening optoelectronics with "Green photonics" opportunities

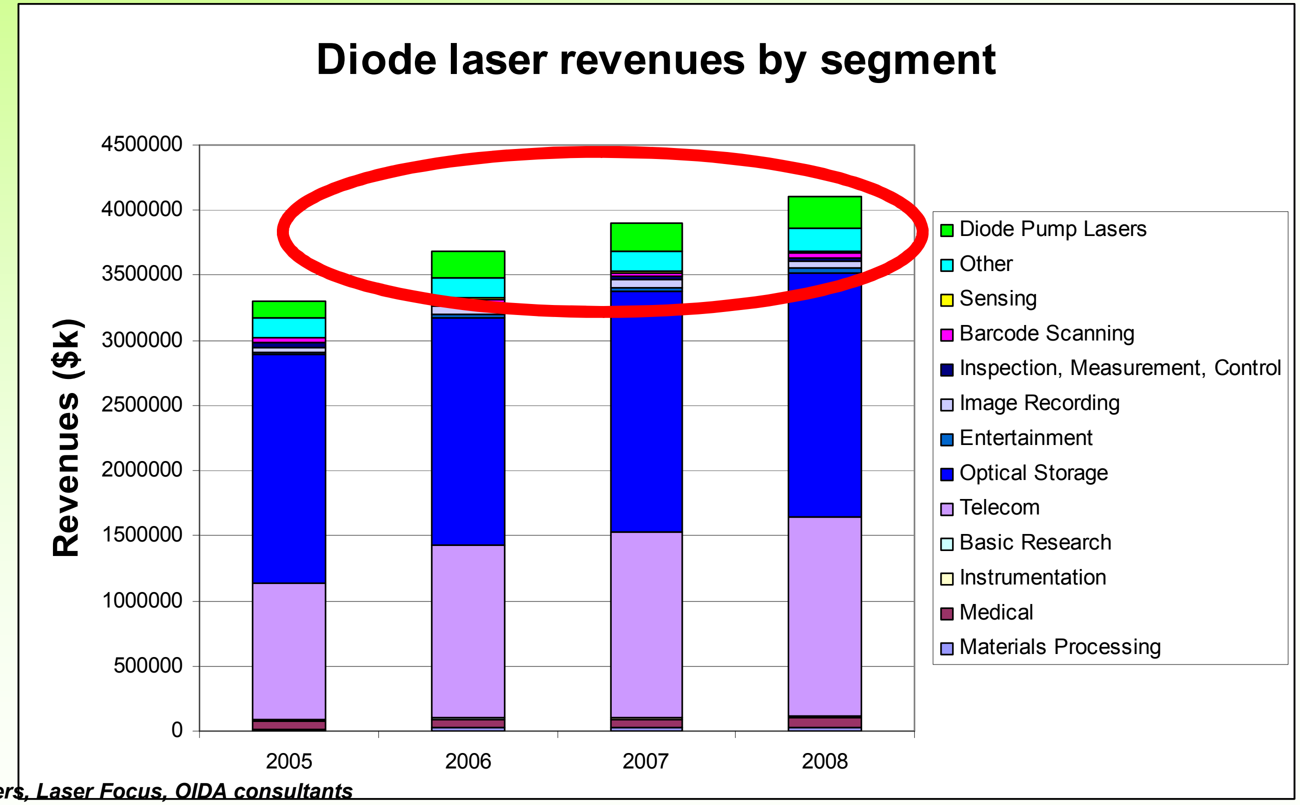


Sources: OIDA

Common platforms for Green photonics…

Diode laser revenues by application

- Optical storage will continue to suffer margin erosion
- Diode pump lasers grow 62.8% in 2006 over 2005

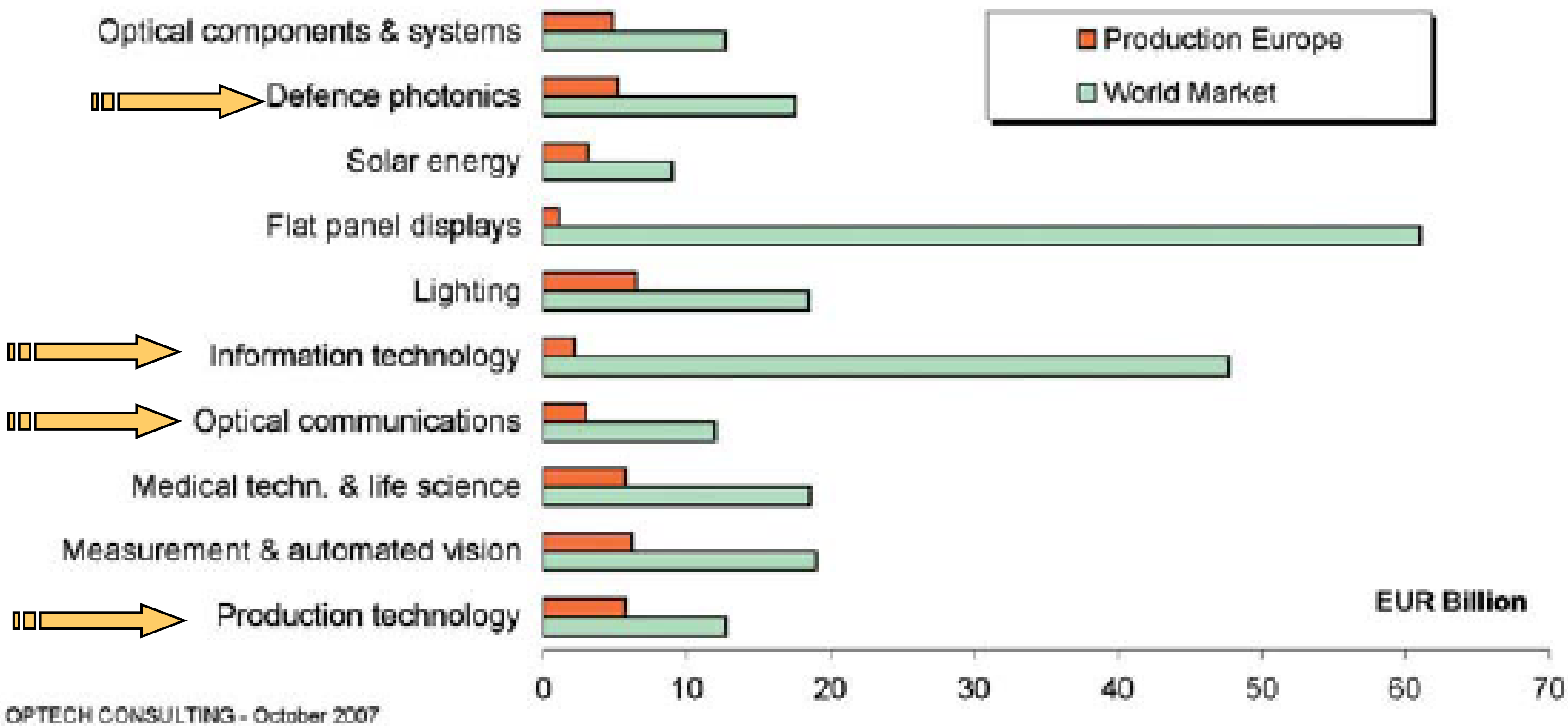


Sources: OIDA, OIDA members, Laser Focus, OIDA consultants

Michael Lebby (lebby@oida.org)

Global Photonic Market: Europe

European Production in a Global Context



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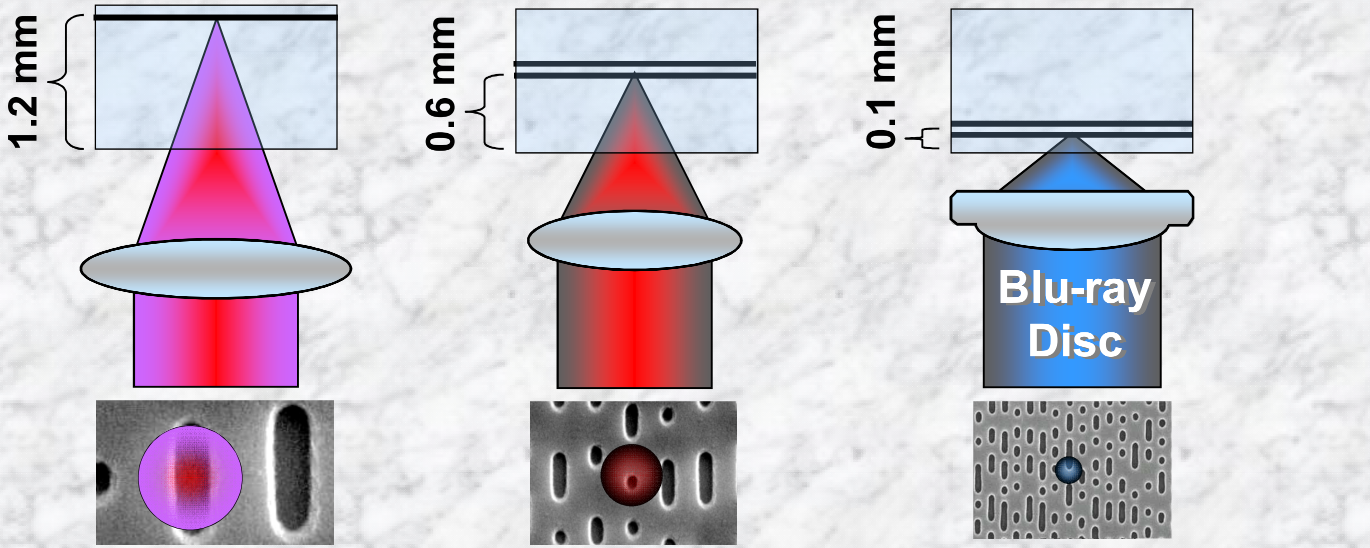
HPL Applications at a glance

Production technology	• material processing, analysis, measurement
Optical communication	• Data transmission, Optical amplification
Defence & Aerospace	• Communication (inter satellite,..), distance measurement, countermeasure, target designation, Illumination, LIDAR,...
Information Technology	• Optical storage, printing, marking, display
Medical	• Aesthetics (Skin treatment,..), surgery, therapy (PDD -Photodynamic disinfection-, PDT -therapy-,..), ophthalmology, Cancer treatment

High Power Diode Laser Applications: Information Technologies

Progress of Optical Storage

	CD	DVD	BD
Wavelength	780 nm	650 nm	405 nm
NA	0.45	0.60	0.85
Capacity	700 MB	4.7 GB (1 layer) 8.5 GB (2 layers)	25 GB (1 layer) 50 GB (2 layers)

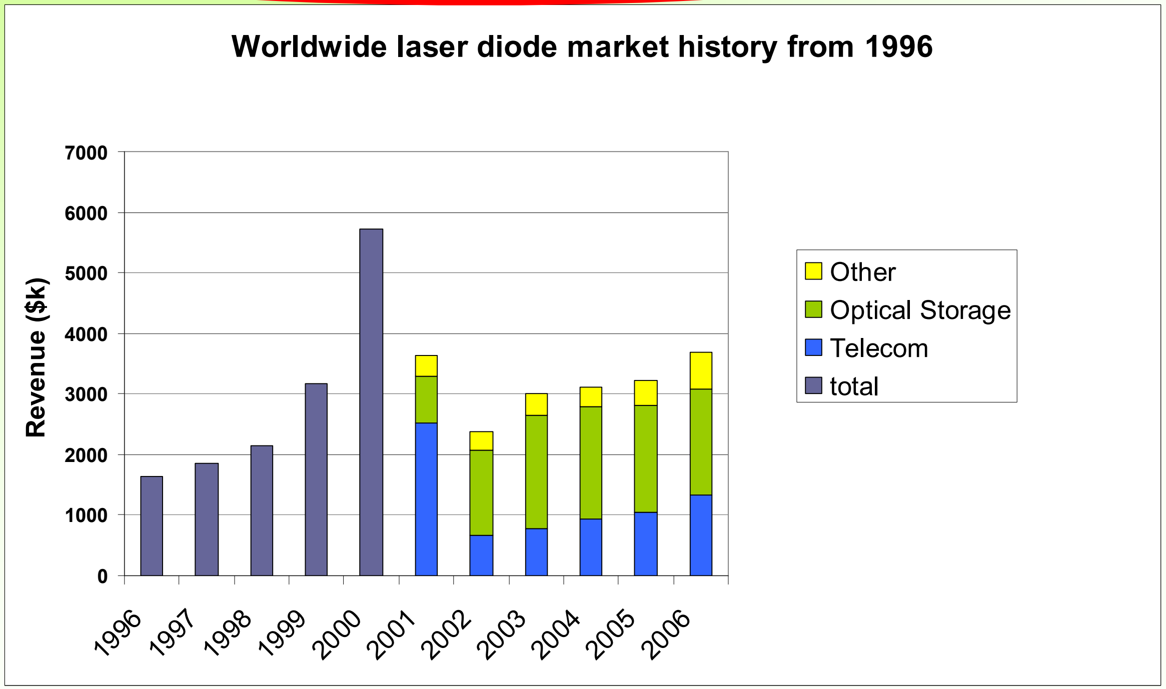


Track pitch 1.6 μm 0.74 μm 0.32 μm

High Power Diode Laser Applications: Communication Technologies

Diode lasers will struggle to grow revenue

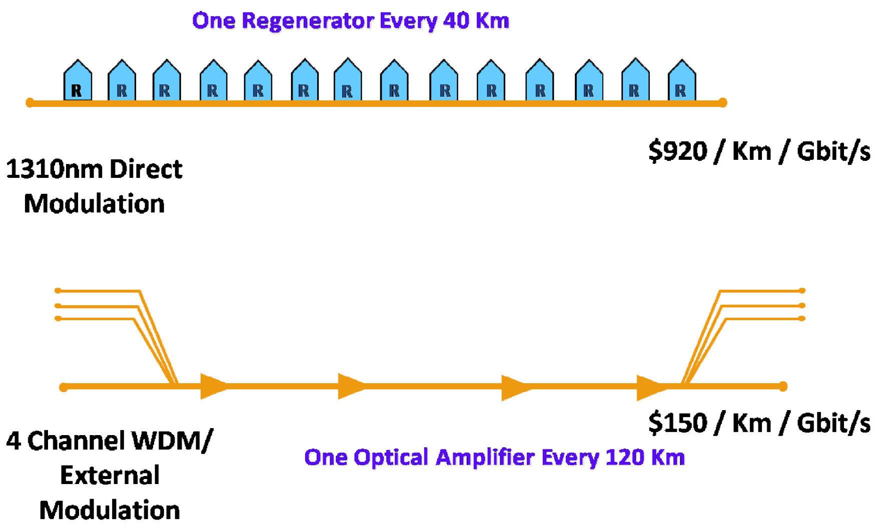
- Telecom experiencing margin erosion
- Optical storage squeezed out by flash



Sources: OIDA, OIDA members, Laser Focus, OIDA consultants

IBM Research Laboratory: 980 Diode Laser

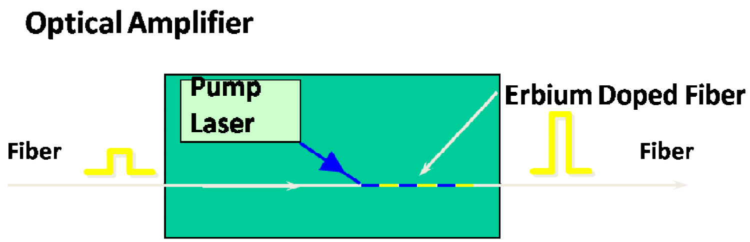
Disruptive Technology:



Today:

A few hundred channels at 10Gb/s over a few thousand km!

Magic Fiber: Erbium doped fiber

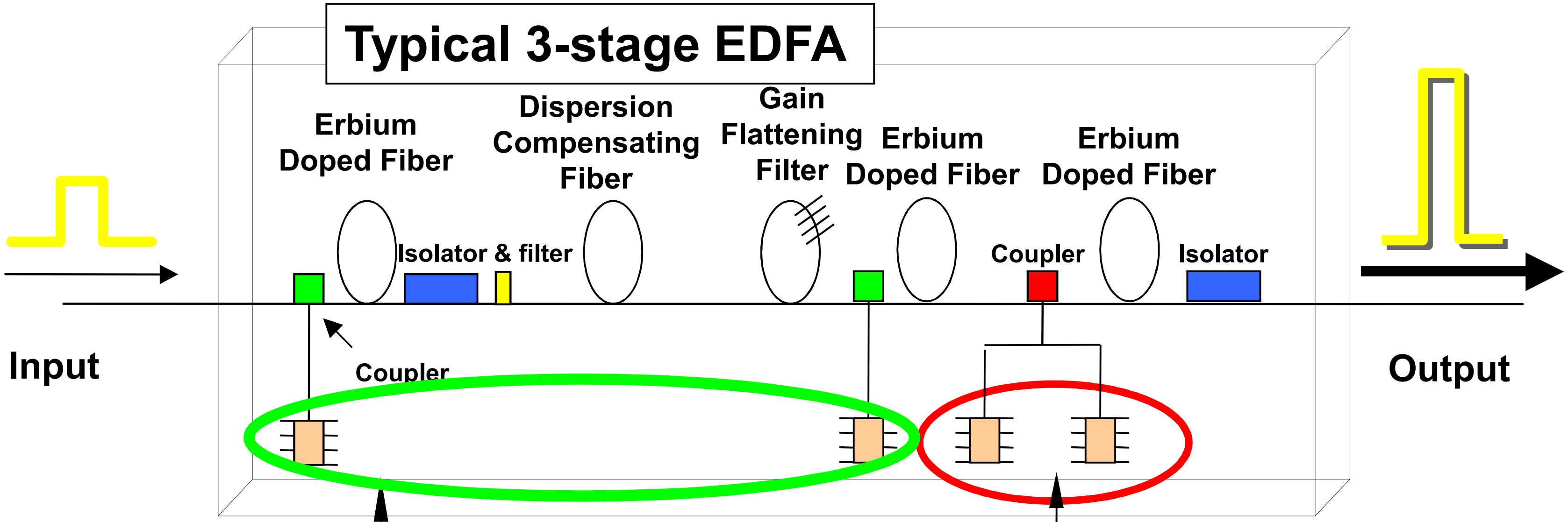


Optical Amplifier:

980nm pump laser as power supply

We were the only laser supplier for high power and high reliability

Why High Power 980nm Pumps?



980 Pumps:
- **Advantage:**
  - **Low noise figure (3 level)**
  - **Low heat load**
  - **High laser efficiency**
  - **Low cost coupler**
  - **Un-cooled operation**

- **Disadvantage**
  - **Lower optical power conversion efficiency**

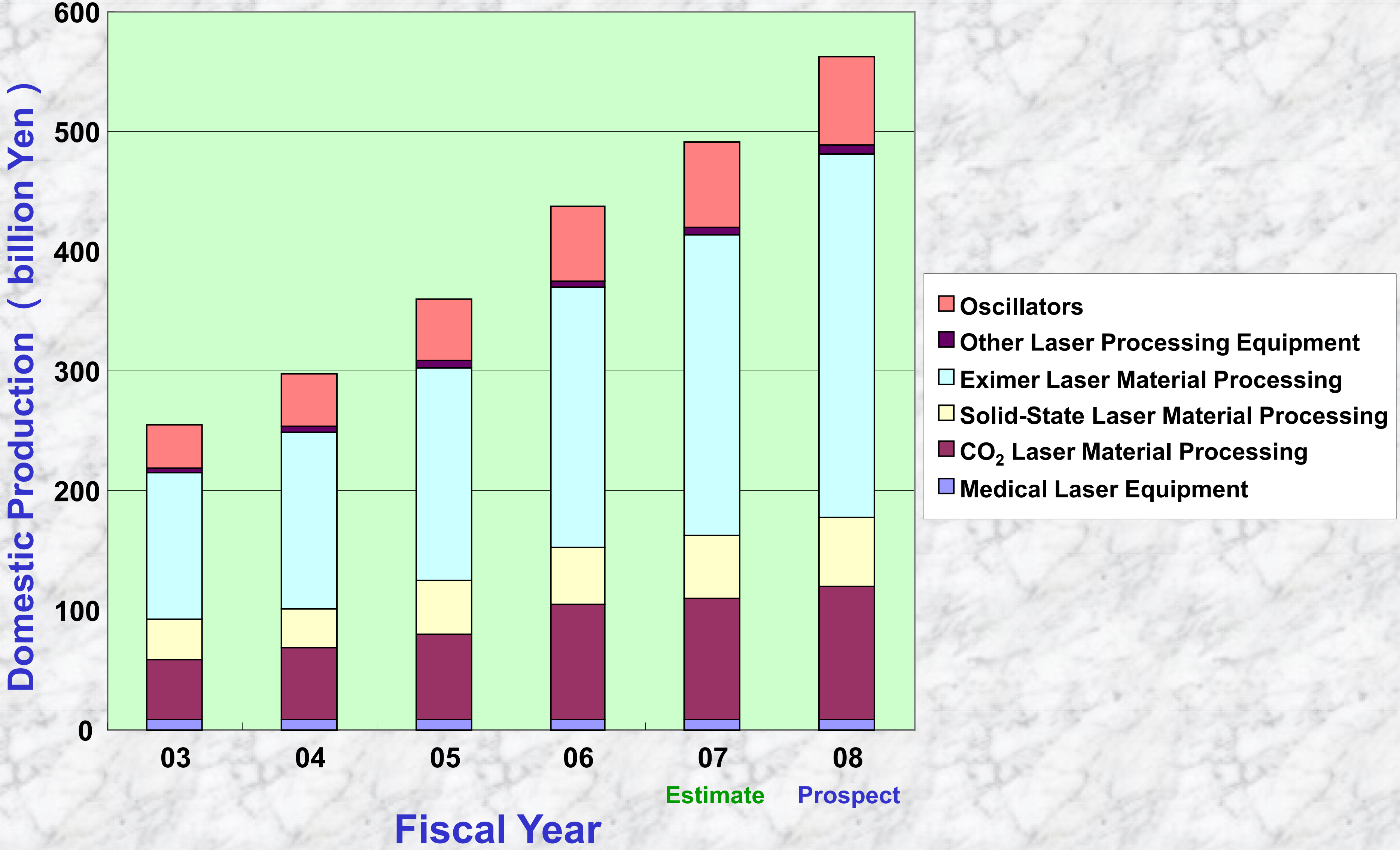
1480 Pumps (now 980nm !):
- **Advantage:**
  - **higher optical conversion efficiency**

- **Disadvantage**
  - **Increased noise figure**
  - **More expensive coupler**
  - **High heat load, expensive cooling**

High power 980 pumps enable low cost EDFAs

High Power Diode Laser Applications: Production Technologies

Domestic Output of Laser Processing



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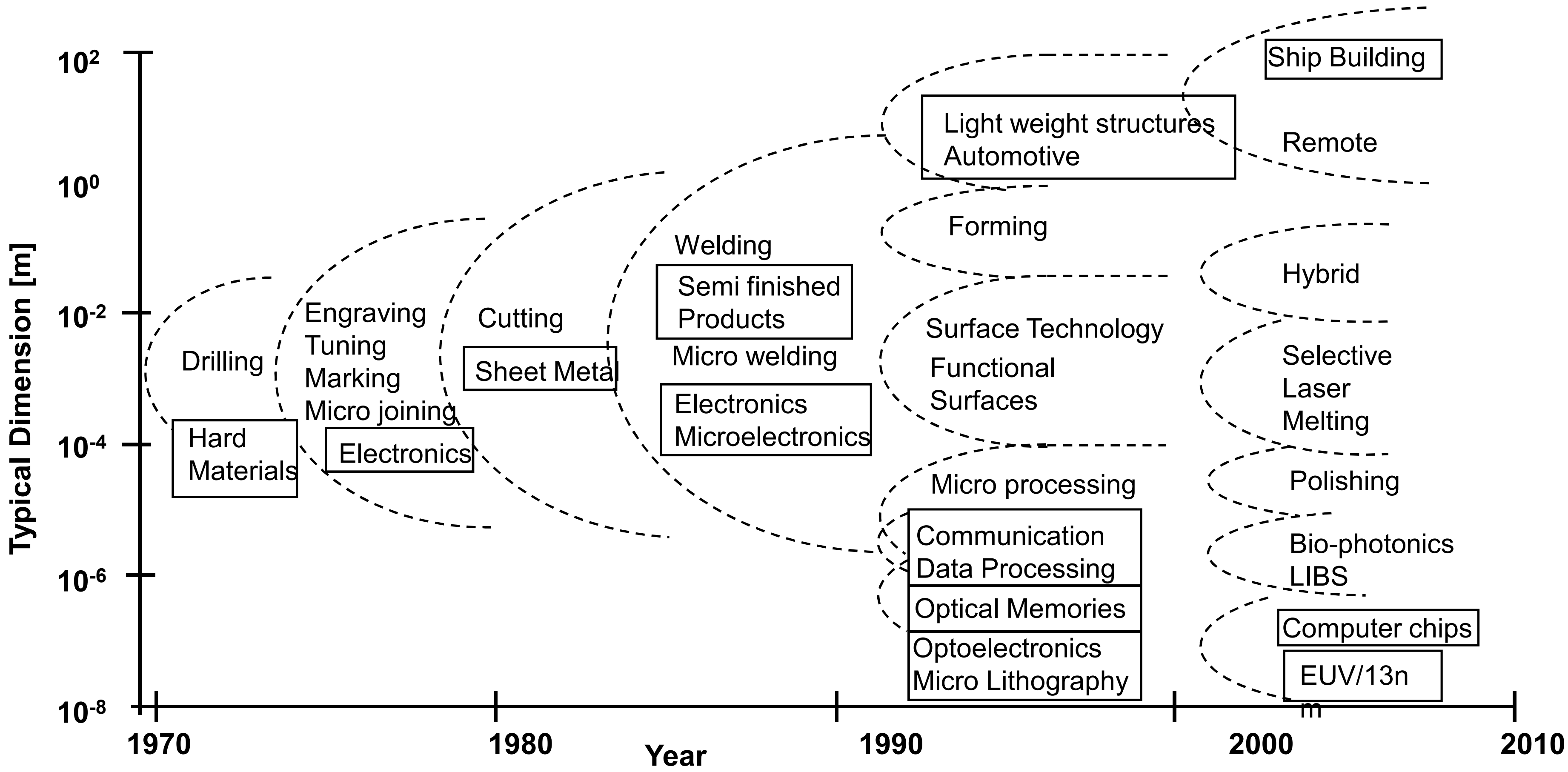
Production Technologies: Geometric scaling of material processing



Which Laser for which Application?

Source: Prof. Dr. Reinhart Poprawe, ILT (AKL 2008)

Production Technologies: Welding

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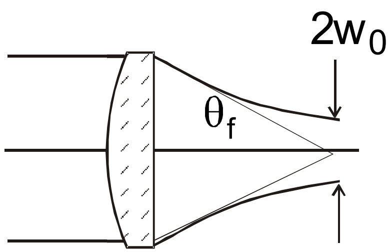
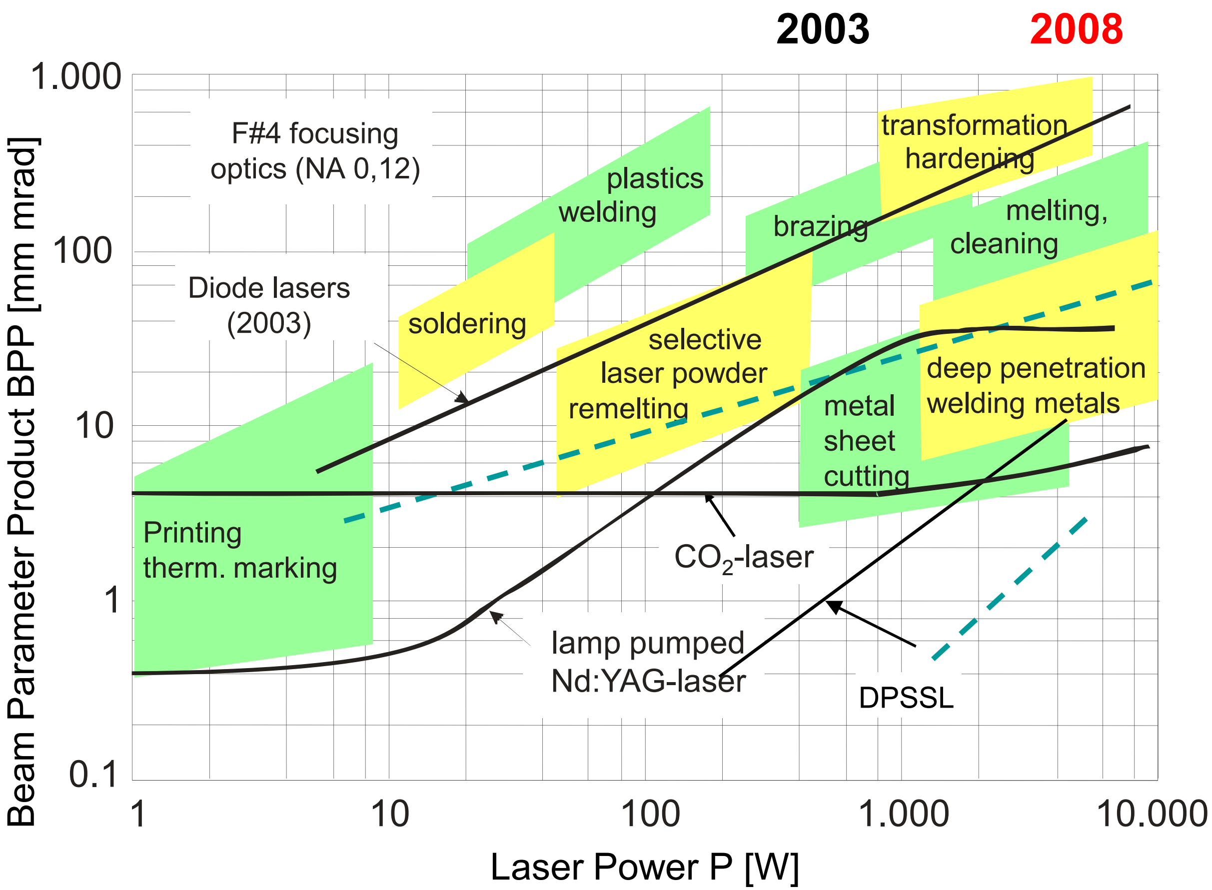
Developing trends for Lasers and their applications

AL-welding (DDL system)



$$BPP = \theta \cdot w_0$$



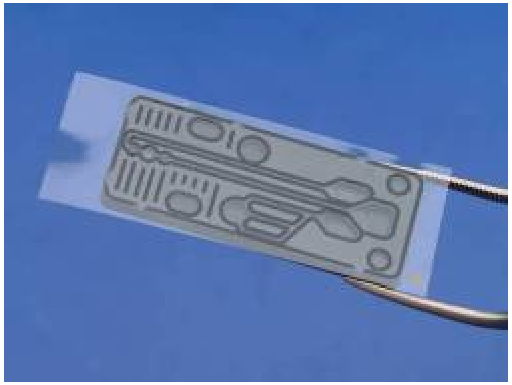
Source: Prof. Dr. Reinhart Poprawe, ILT (AKL 2008)

Application example: welding of thin foils

Foils
- -Polypropylen (PP) transparent and black thickness 100 µm

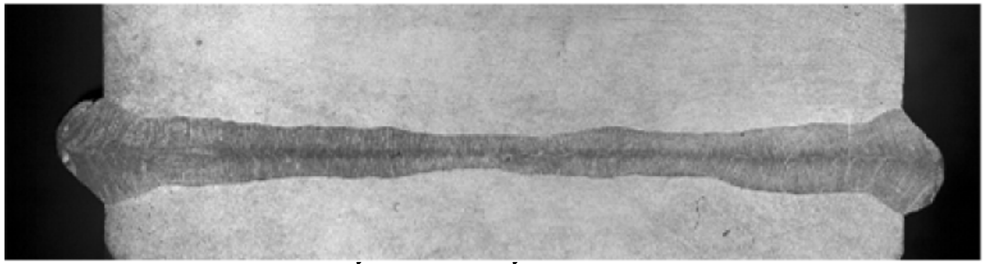
Microfluidic device
- - PMMA or PP sealing foil (75 µm)

P= 1,4 – 5,9 W
v= 50 to 250 mm/s
d_0= 70 µm
$d_{weld\ seam}$= 150 to 500 µm

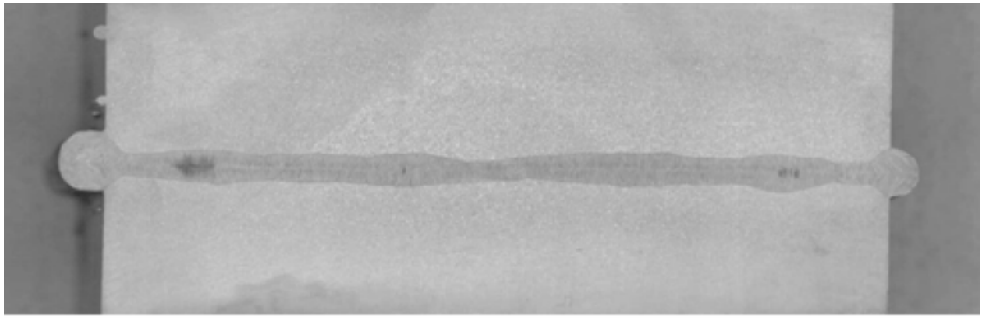


Source: Prof. Dr. Reinhart Poprawe, ILT (AKL 2008)

Double sided butt joint 30kW



2” stainless steel



P=30 kW, v= 2,0 m/min

Single Mode Welding

Power: 3kW

Stainless Steel

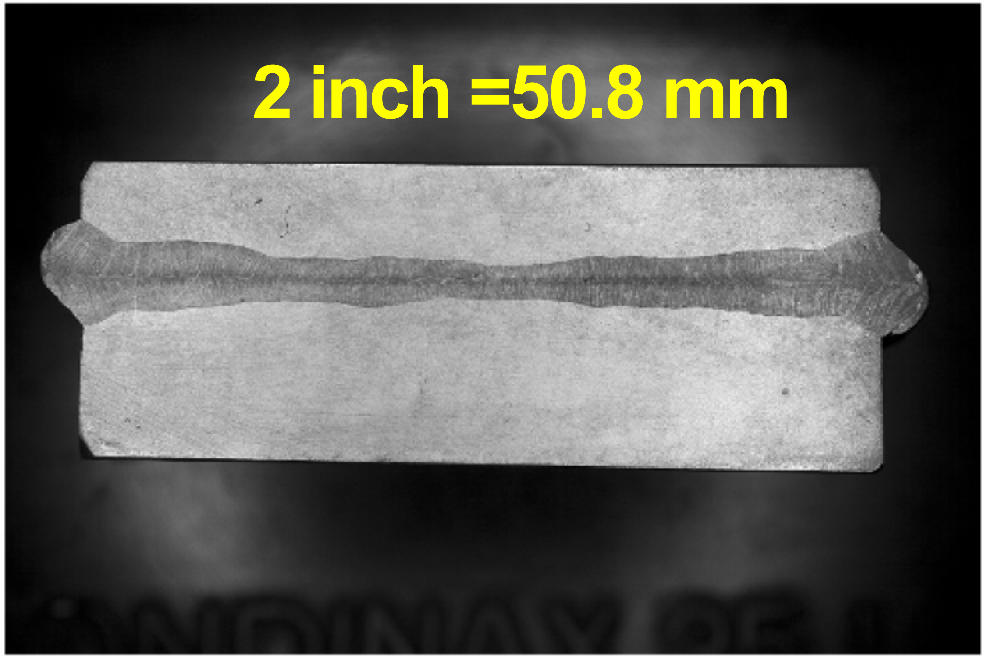
v=0.5m/min
Depth=1 3mm
Width≈1mm

v=10m/min
Depth=6mm
Width≈0.2mm !!!

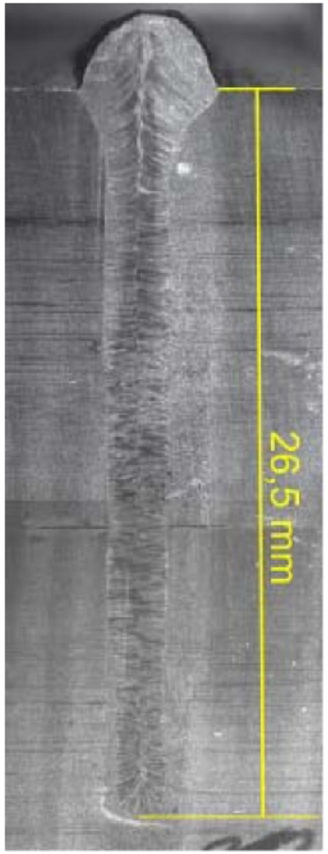
Source:

Laserinstitut
Mittelsachsen e.V.

Thick Section Welding YLR20000



Butt joint 2 inches (50.8 mm)
Double sided welding
Stainless steel 1.4301

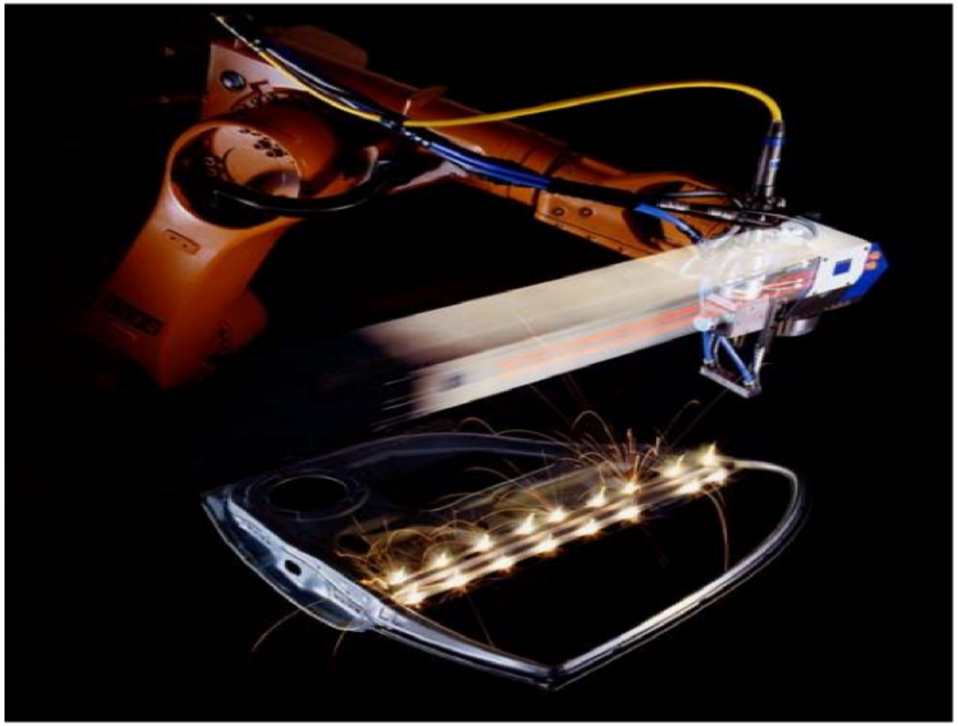


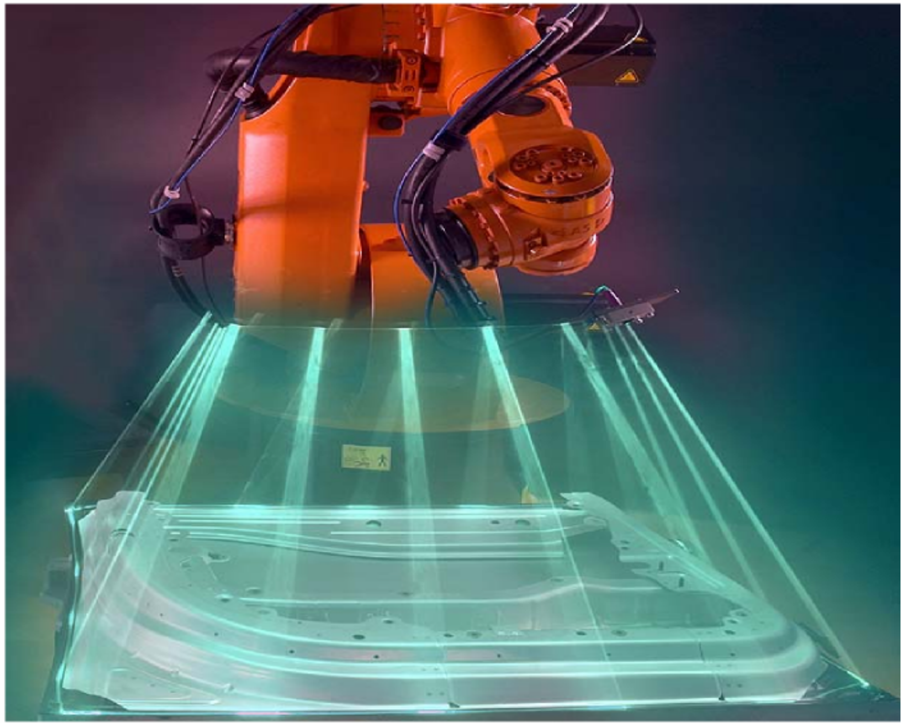
Overlap joint 2x 15 mm
Stainless steel 1.4301

Scanner und KUKA ***RoboScan*** . *Scanner and KUKA **RoboScan***

Bewertungskriterien:

Versatzgeschwindigkeit - Schweißgeschwindigkeit - Taktzeit - Linienkonzept - Komponentenflexibilität - Arbeitsabstand - fixe und variable Kosten - Zugänglichkeit - Nahtgeometrie - Bauteilflexibilität - Lasernutzung - Schweißqualität





Assessment criteria:

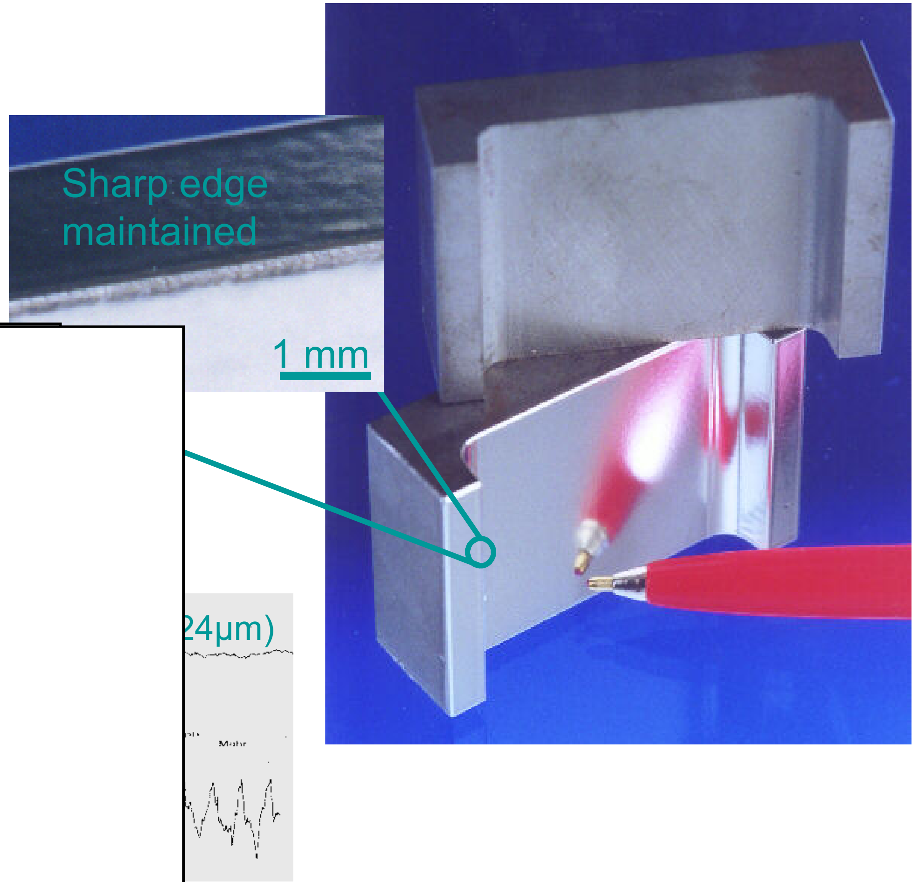
cross velocity - welding speed - cycle time - line concepts - flexibility of components - working distance - fix and variable costs - accessibility - seam geometry options - part flexibility - efficiency of laser source usage - weld quality

Production Technologies: Surface Finish

Application example: laser polishing

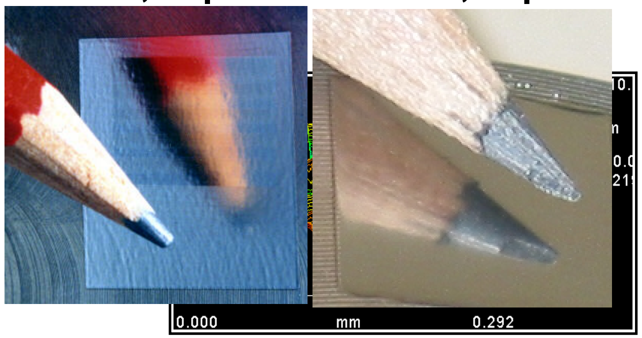
Materials: 1.2343, 1.2344, 1.2316

Initial state:
milled, eroded,
grinded



2002
Ra = 0,35 µm

2008
Ra = 0,09 µm



Source: Prof. Dr. Reinhart Poprawe, ILT (AKL 2008)

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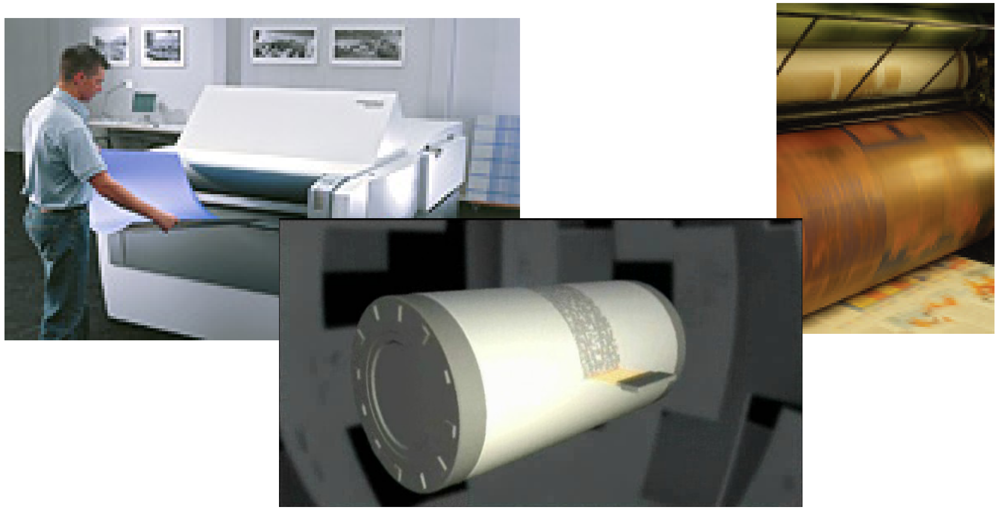
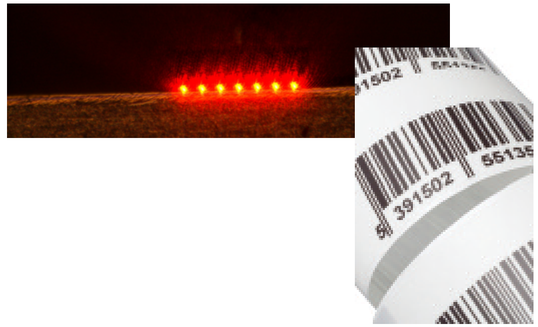
Information technology: optical storage, printing, display





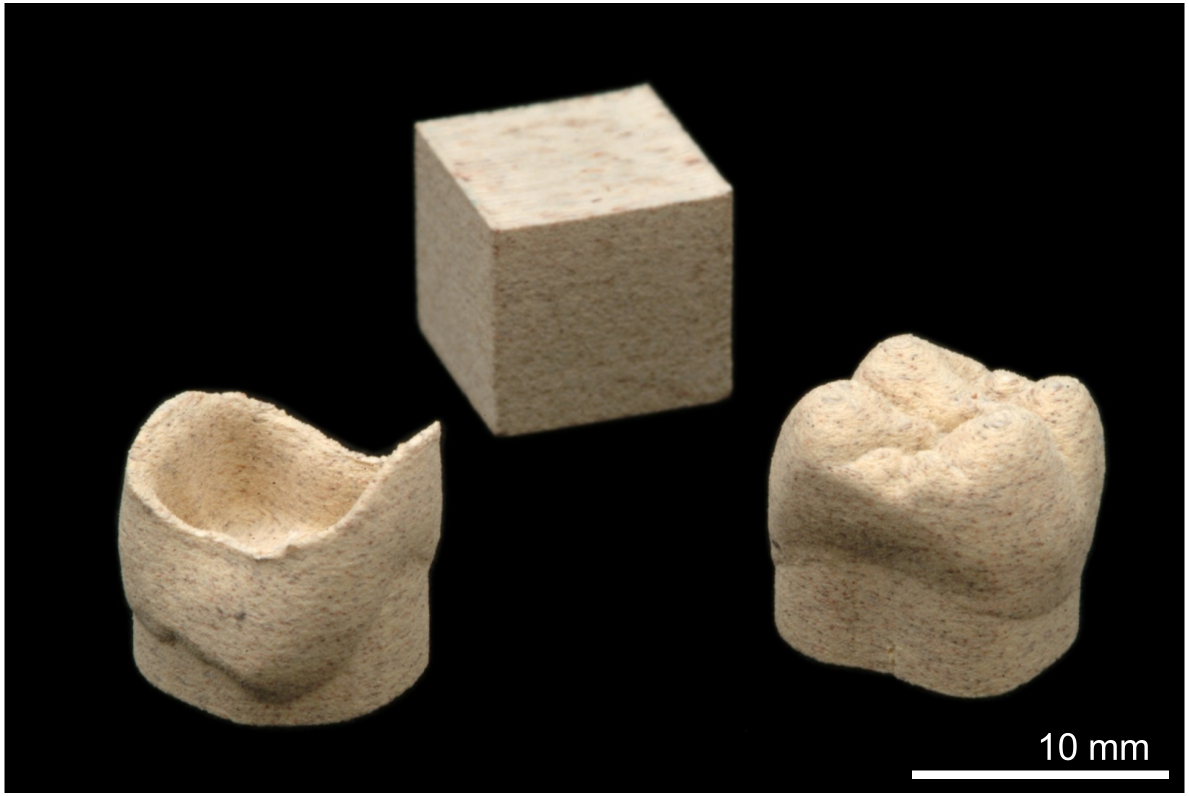
CTP Printing

- Computer to plate (CTP) Printing
- Digital printing
- Display (RGB) technology
- Rear projection TV

Production Technologies:
Rapid Prototyping

Application Example SLM of ZrO_2-based Ceramics

- **Zirconium oxide (ZrO_2): max. bending strength, resistance to wear and tensile strength**
- **Principle of Selective Laser Melting (SLM): Ceramic powder is fully molten (no sintering)**
- **Potential Application: Production of full-ceramic dental prostheses**

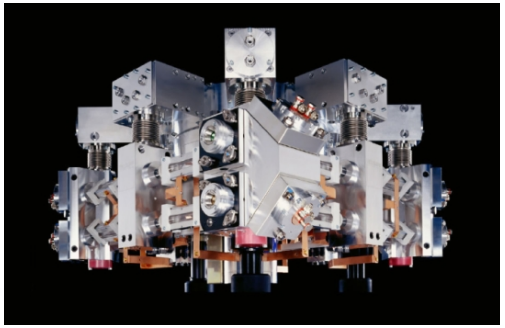


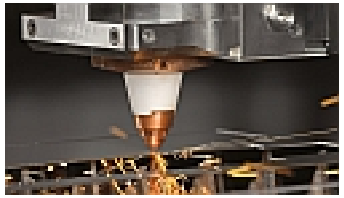
SLM demo parts

Source: Prof. Dr. Reinhart Poprawe, ILT (AKL 2008)

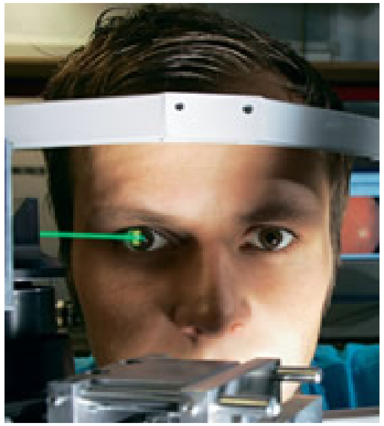
Production Technologies: Cutting

CO2

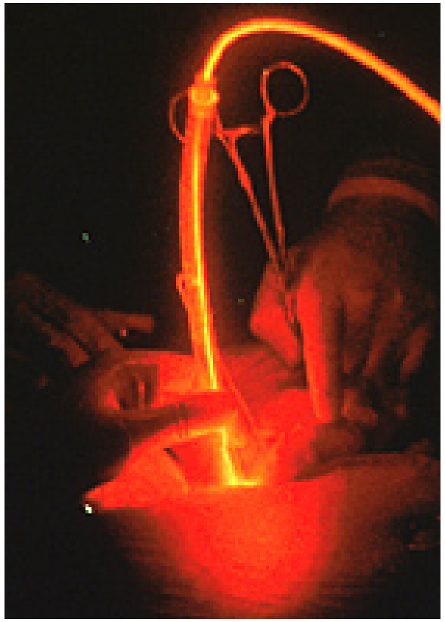




Medical applications:



Ophtalmology



Surgery

Hair removal

Before

After

Skin Treatment: Tattoo / Hair Removal

Before

After

- Acne treatment
- Photodynamic Therapy (PDT)
- Photodynamic Disinfection (PDD)
- Dental

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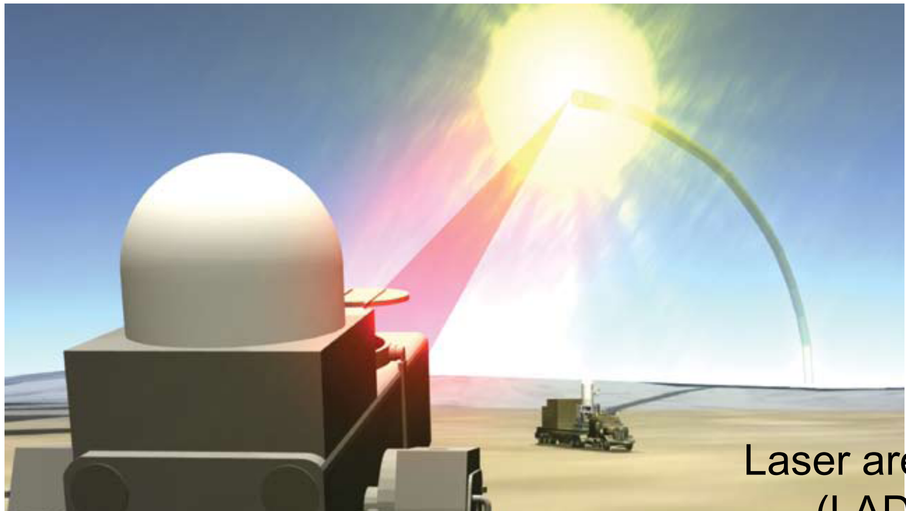
Defence and homeland security applications: slowly evolving

Laser countermeasure system against heat-seeking missiles

Example: Directional Infrared Countermeasure (DIRCM) from Northrop Grumman (public Information)

Distance measurement,
Target designation



- Laser fuses
- Illumination
- Detection of chemicals

Laser area defence system (LADS from Raytheon)
(public Information)

Photonic Tools:

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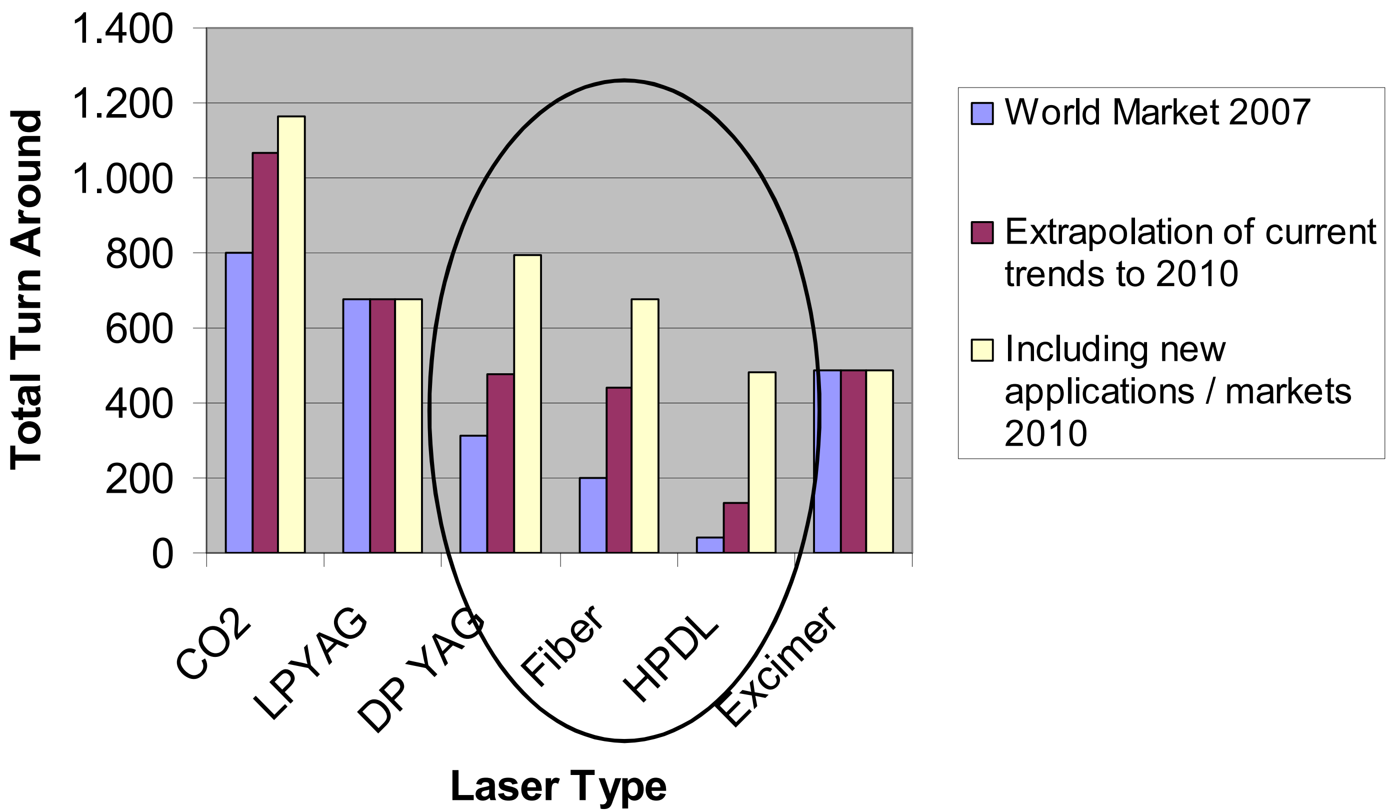
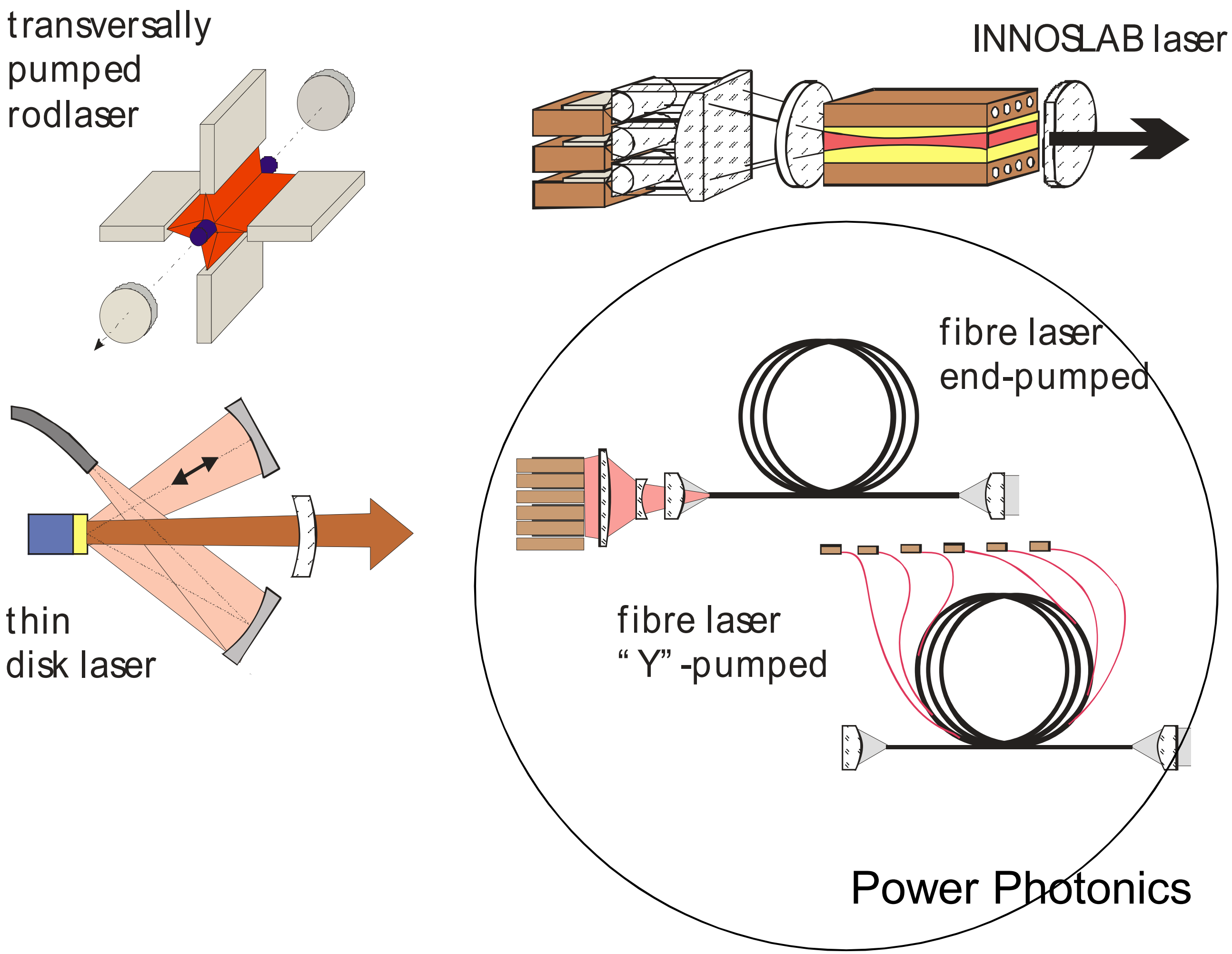
Laser Market Development by Laser Type



Source: Prof. Dr. Reinhart Poprawe, ILT (AKL 2008)

Photonic Tools: Overview

Laser system design principles



All based on the same design principle requiring

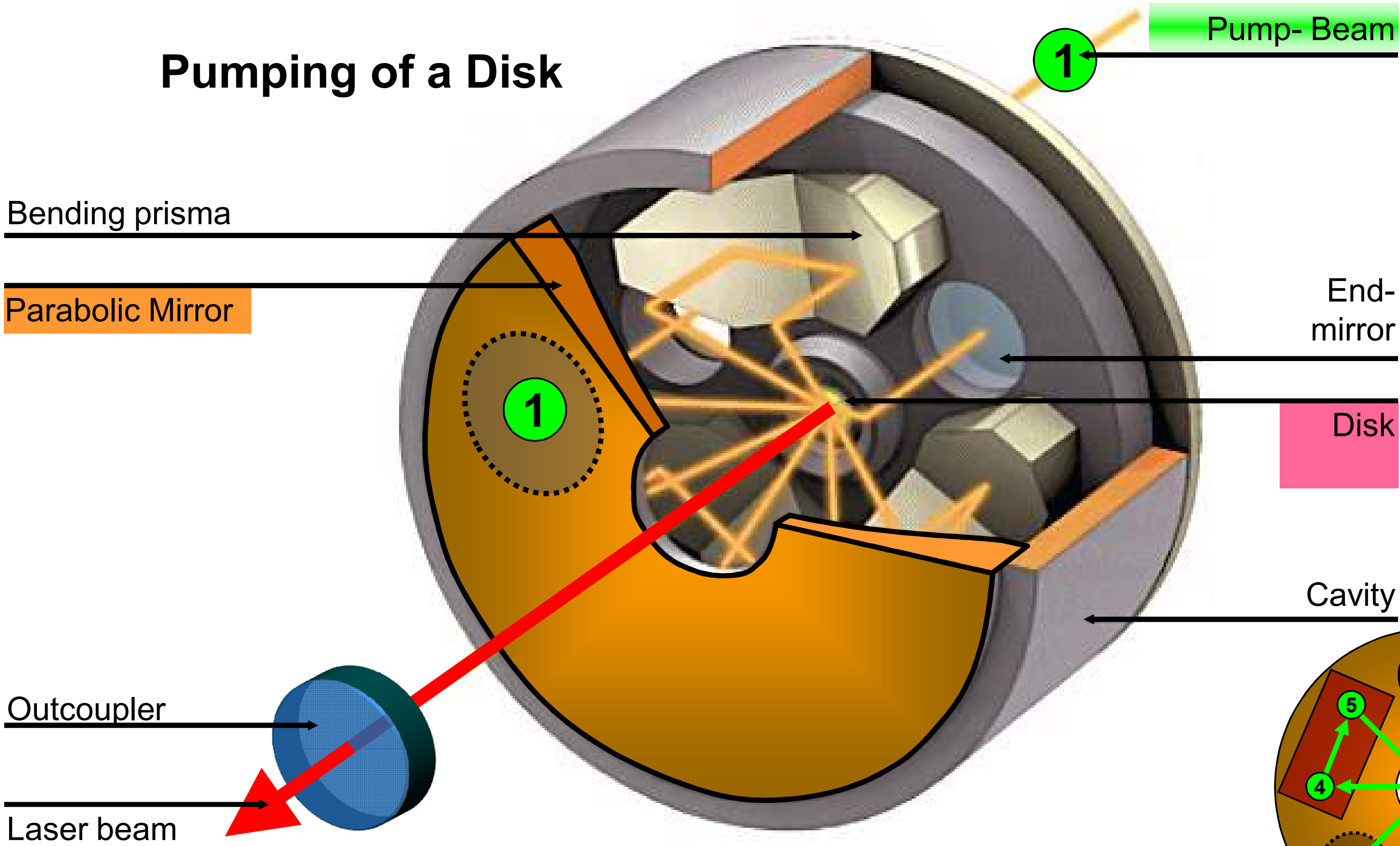
- **Mirrors (Cavity)**
- **Gain medium**
- **Pump source**

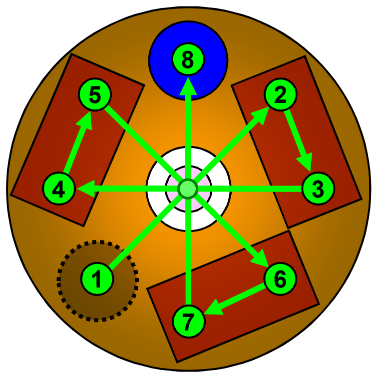
Extension...
amplifier technology

Source: Prof. Dr. Reinhart Poprawe, ILT (AKL 2008)

Photonic Tools:
Disk Laser

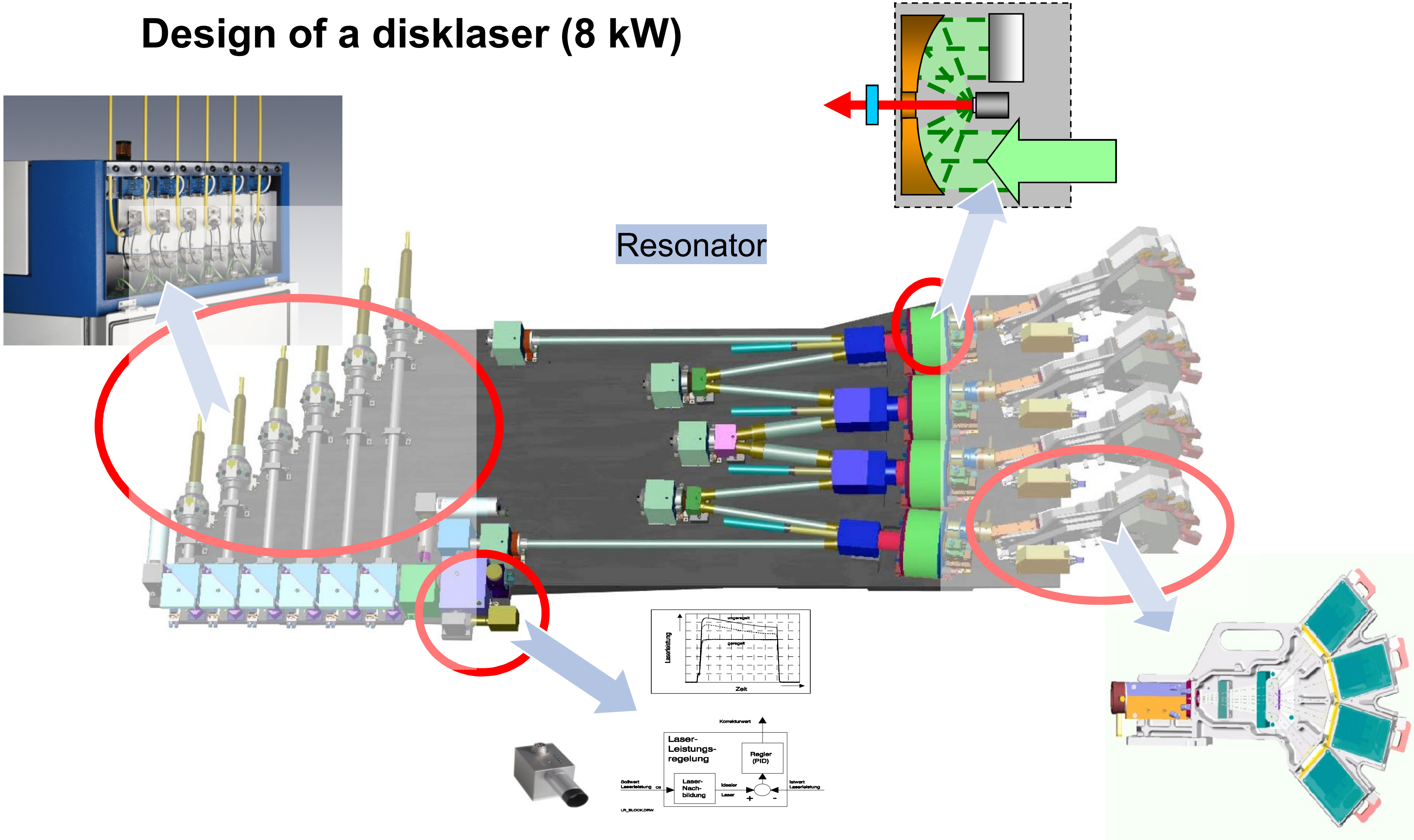
Pumping of a Disk

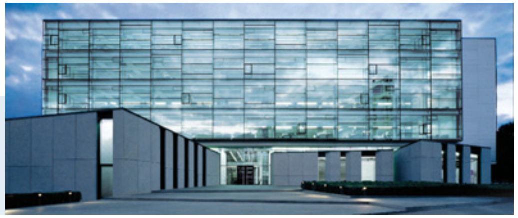




Actually: 20 passes of the pump light through the disk!

Design of a disklaser (8 kW)



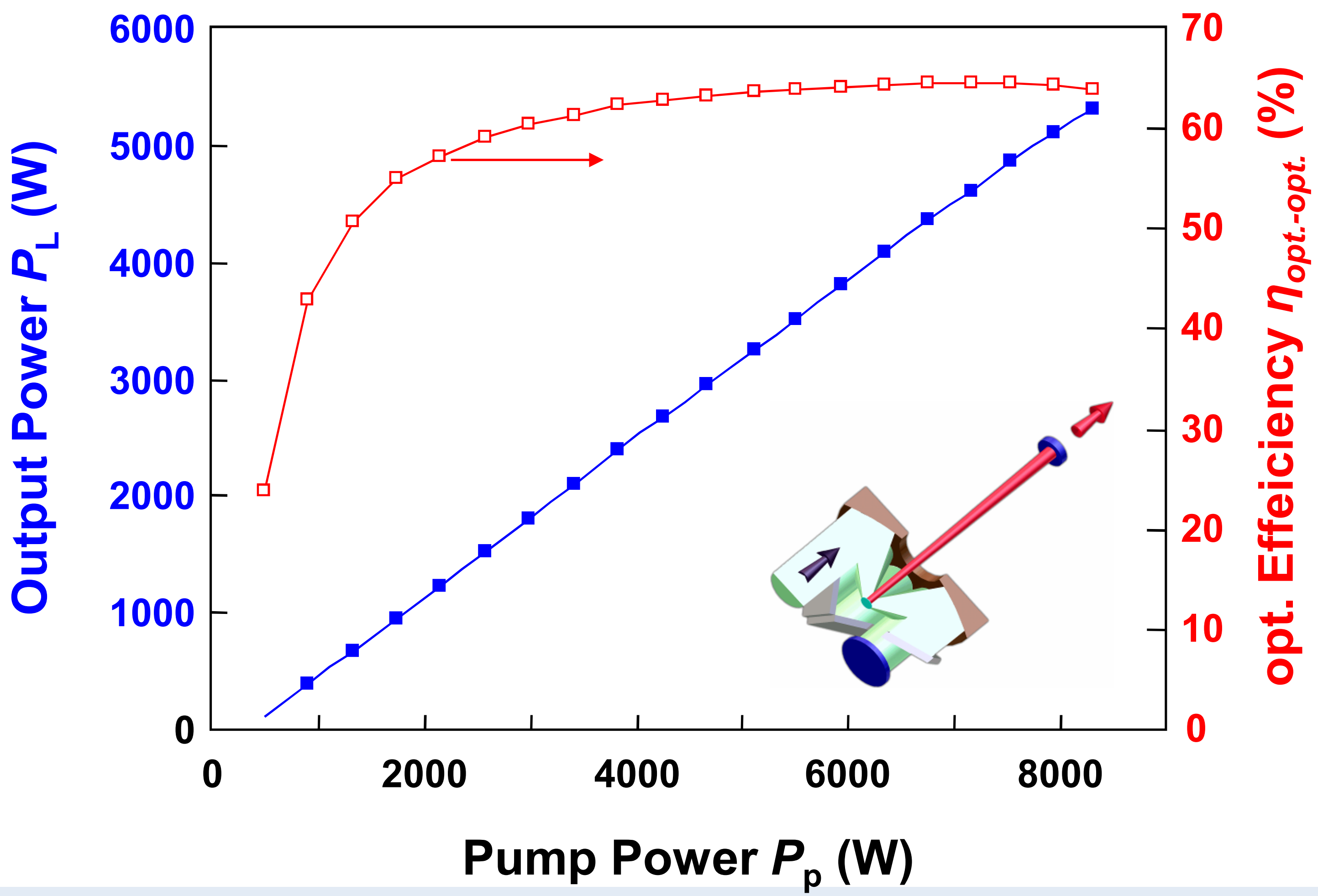


Disklaser: TruDisk

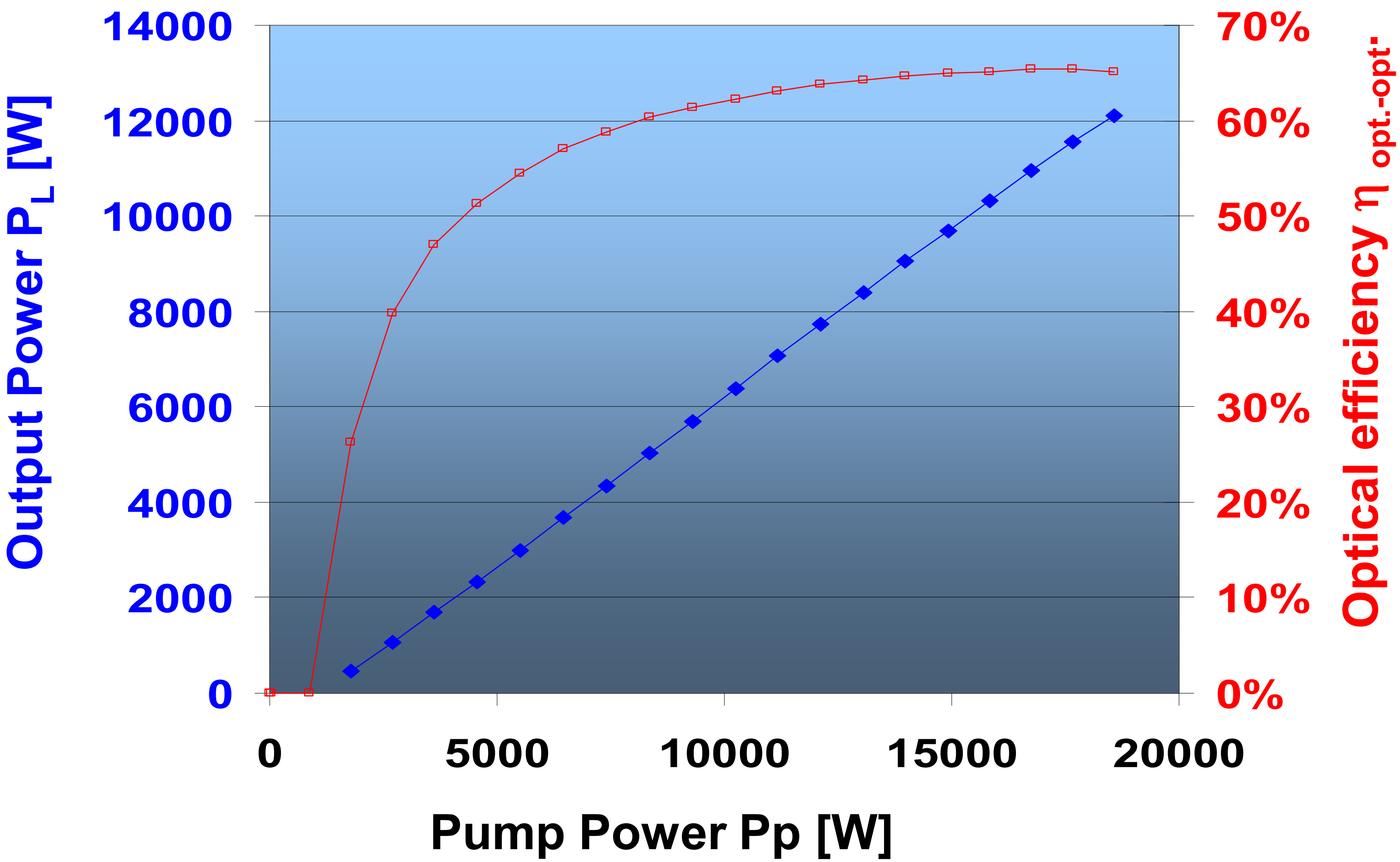
TruDisk 1000 **TruDisk 8002**

AHPSL 2008 Seminar #1

> 5 kW Output Power per Disk



TruDisk 10003 – 4 disk resonator



Power Photonics

Fiber combiner
Fused and Proximity

Fused: (6+1)*1

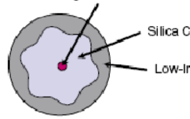


Figure 2 **Cross-section of double-clad optical fiber for cladding pumping.**

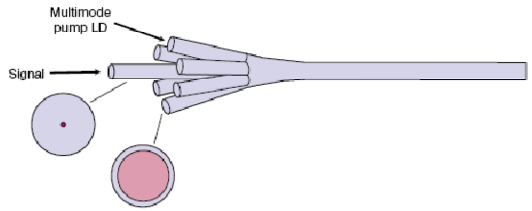
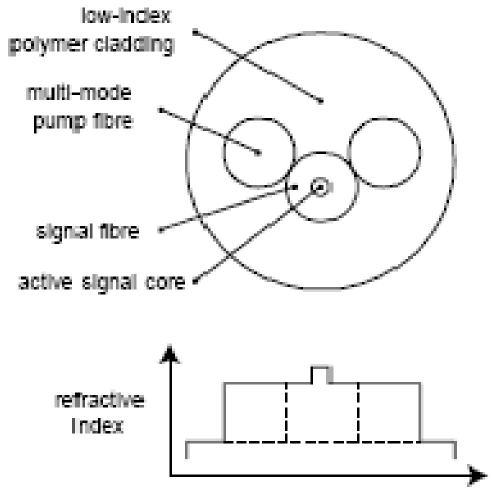


Figure 3 **Schematic of tapered fiber bundle.**

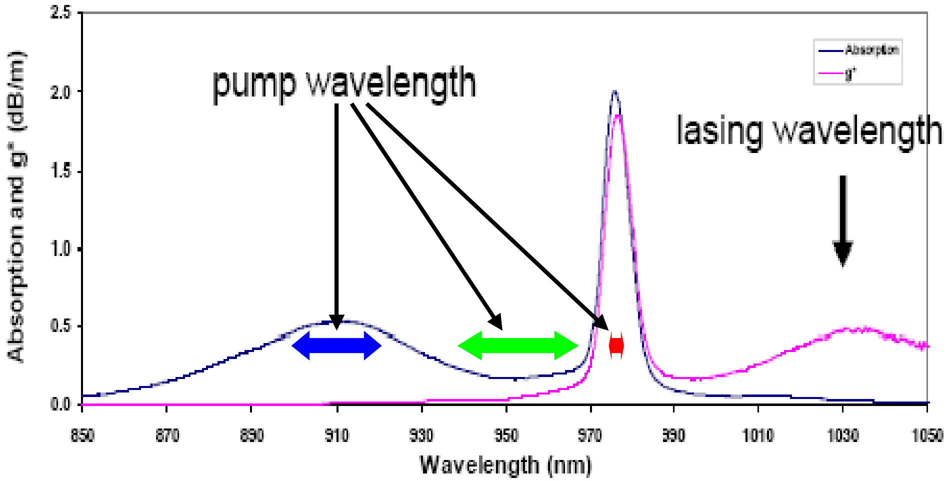
	Fiber	NA
Signal input	HI 1060	
Pump Ports	6*105um	0.22
Output	20um/400um	0.06/0.46

Proximity: (2+1)*1



- Fused can be extended to beyond 20 inputs
- Proximity needs high brightness pumps

Yb fiber wavelength: 9xx bands



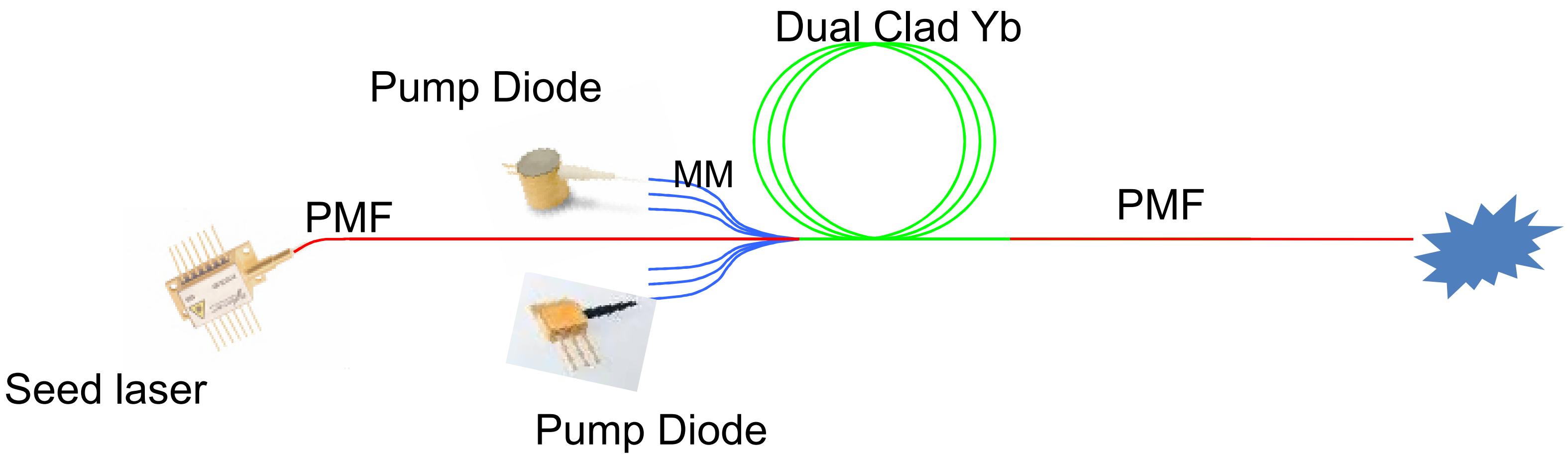
Wide pump band: 870nm to 980nm

***Blue band (915nm)**: Good absorption, wideband*
- *Preferred for lower power, high gain stage*

Green band (940nm..960nm): Lowest absorption, wideband, high optical conversion
- Preferred for very high power stage

***Red band (976nm)**: Highest absorption, narrow width*
- *Preferred for high gain amplifiers and q-switched lasers with short fiber (SBS)*
- *Pump diode challenge: Diode wavelength control (+/-2nm) necessary*

Fiber Laser: MOPA



- Seed laser
  - Fiber laser: Good spectral control
    - Need external modulators (Pockels Cell)
  - Diode laser: Excellent dynamic control
    - FP laser have poor spectral control, of no concern
    - DFB have excellent spectral and dynamic control

- Pumplaser
  - Single emitter broad area MM diode

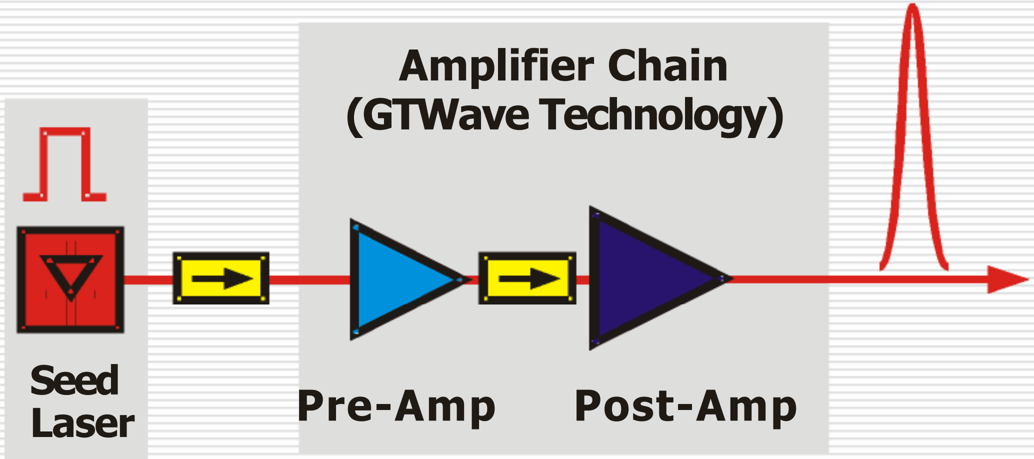
Photonic Tools:
Fiber Laser

Yb fiber laser

SPI G3 Yb doped Pulsed Fibre Laser 1 064nm wavelength

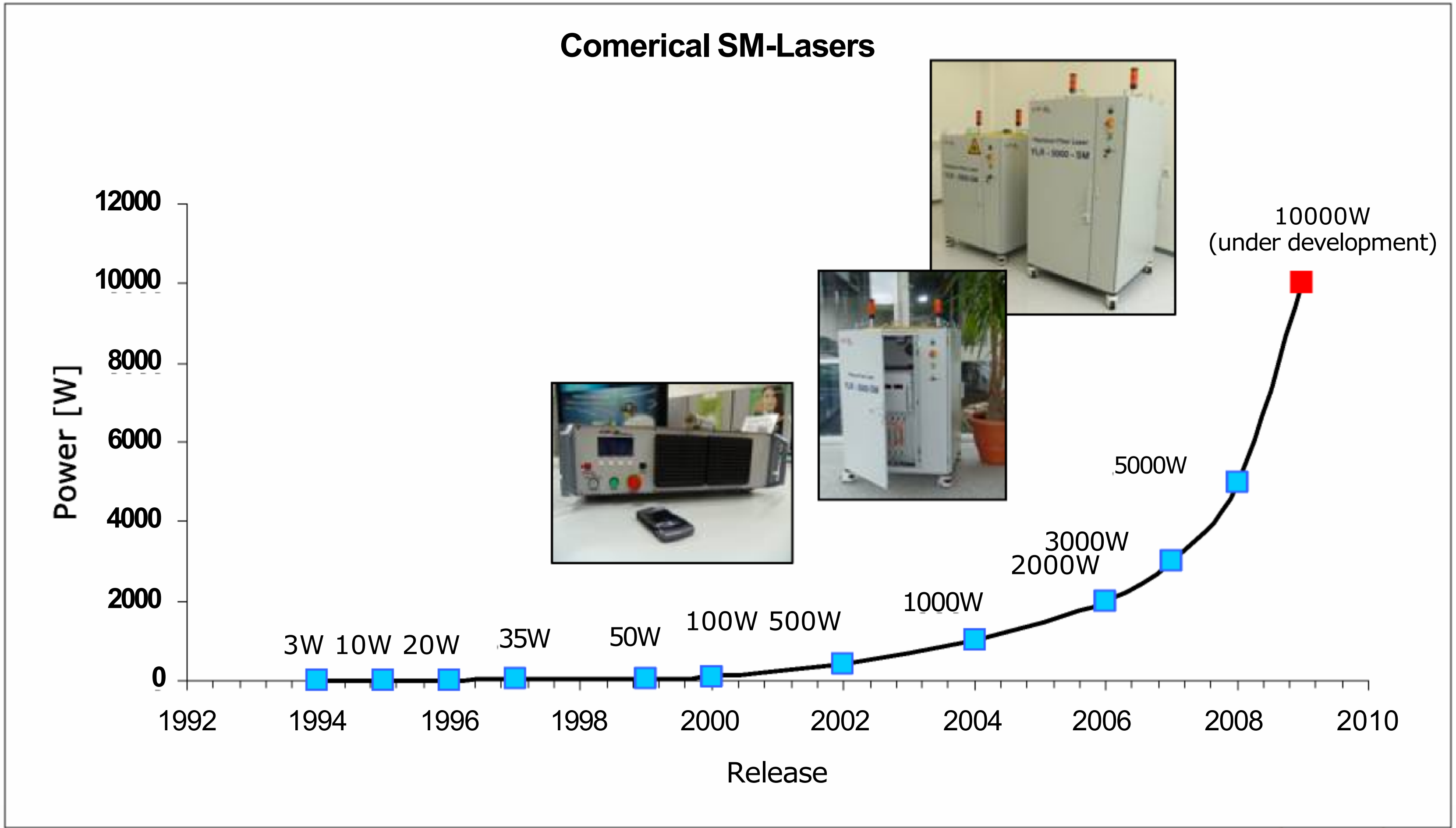
MOPA (Master Oscillator Power Amplifier) architecture

directly modulated Laser Diode

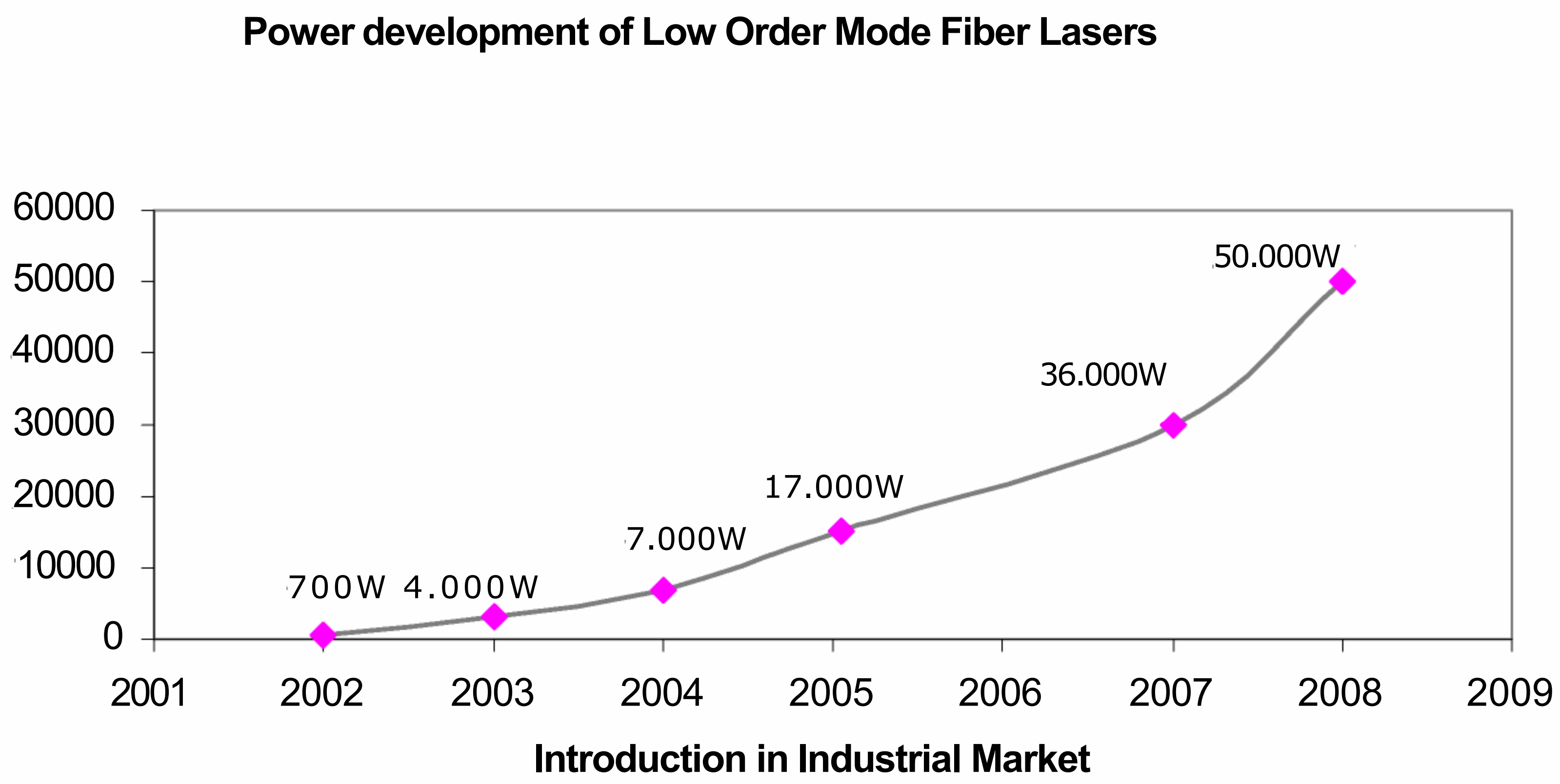


- Average Power: 20W
- Spot size: 40um with x3 Beam Expander, 9mm input beam diameter
- Pulse width: 10-70ns FWHM
- Peak Power: 14kW per pulse
- Power density: up to 1GW/cm^2 for 40um spot size
- Pulse Energy: 0.8mJ max
- Pulse frequency: up to 500KHz, 25 preset pulse waveforms

Status and Development of Single Mode Fiber Lasers



High Power Fiber Lasers - History

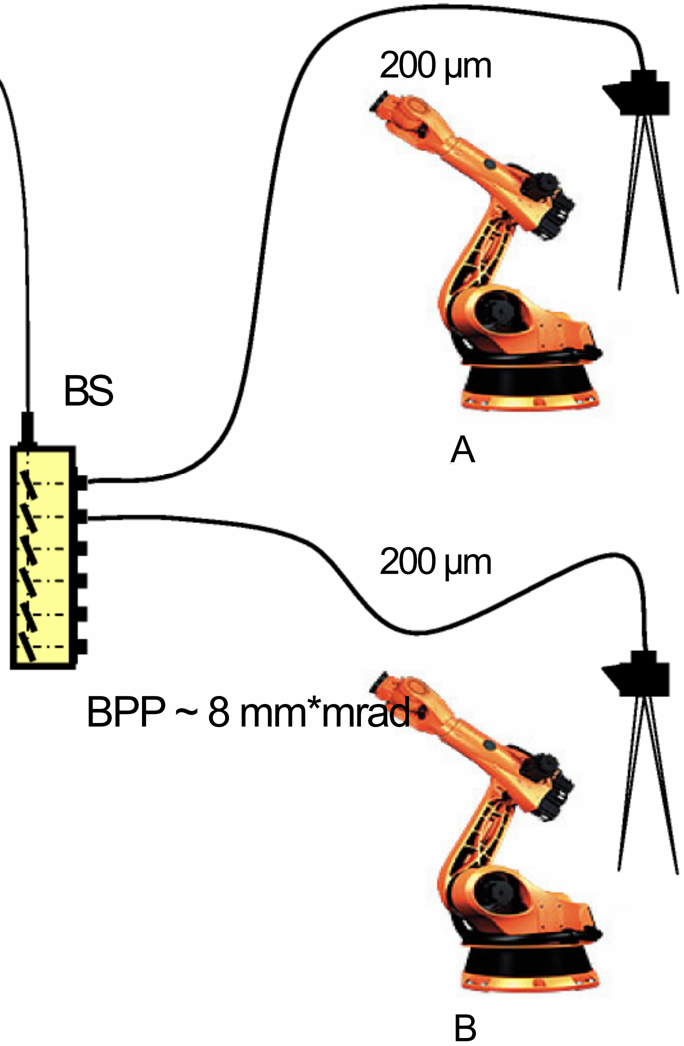


Aktivitäten im FüLas-Projekt - *FüLas project activities*

100 µm

Laserleistung 8 kW
BPP ~ 4.5 mm*mrad

Große Abstände zwischen Laser und Strahlweiche bzw. Bearbeitungszelle



Laser power 8 kW
*BPP ~ 4.5 mm*mrad*

Large distance between laser and beam switch respectively production cell

Single Mode Pump Diode Lasers

- Single Mode Fiber Pump Module
- Pump Diode Beam
- Pump Diode Beam: Slow axis
- Ridge waveguide
- Shift Kink
- Vertical epitaxial structure
- Length Scaling
- Spectral stabilization
- Passivation
- Packaging
- Reliability

- Literature

System Design Requirements

Majority of diode based laser systems have common design requirements:

- Efficient coupling into passive optics elements or an optical fiber (with low NA)
- High wall plug efficiency (low power consumption)
- Good system reliability
- Cost competitive
- Simple to use (cooling, turn on time, robustness,…)

From a diode perspective this relates to various design objectives….

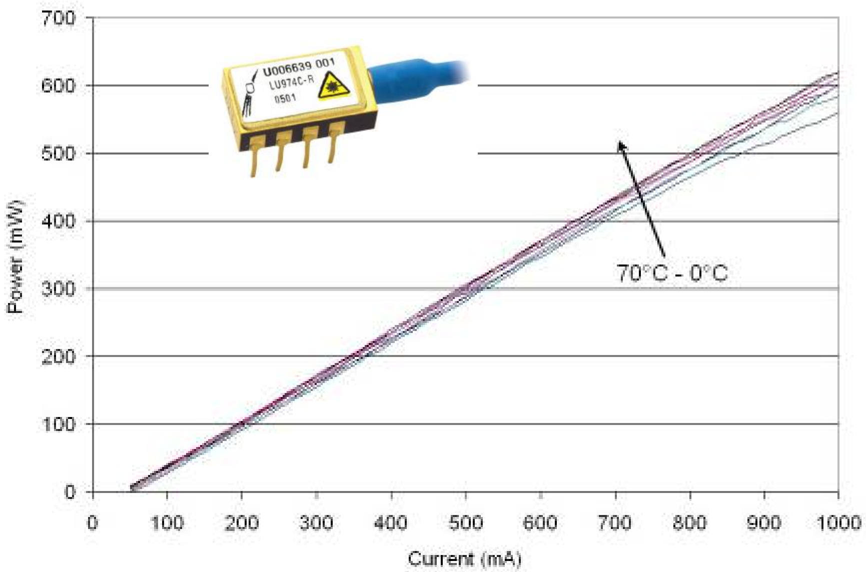
Laser diode design targets

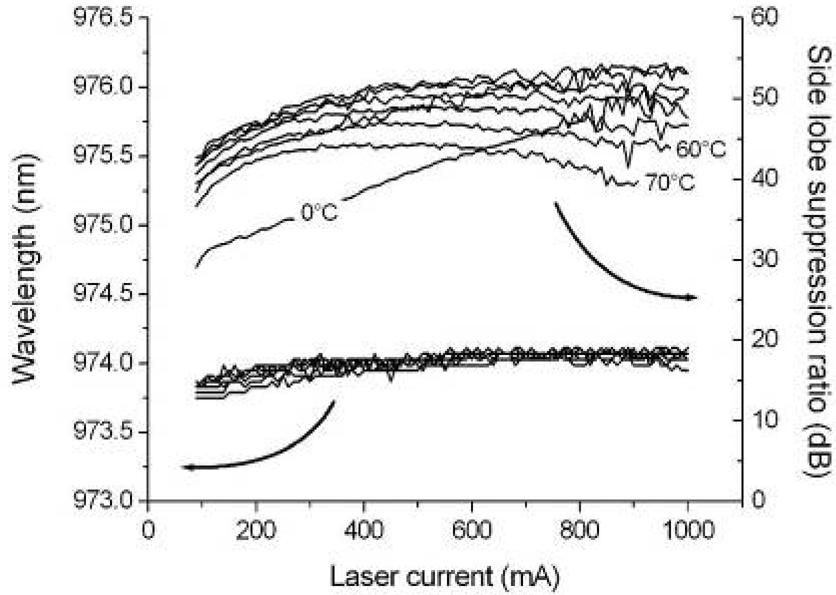
Common design requirements for high power laser (HPL) diodes:

- **High output power**
- **High brightness**
- **High wall-plug and coupling efficiency (low power consumption)**
- **High reliability + robust**
- **Design capable for high volume manufacturing**

Single Mode Fiber Pump Module

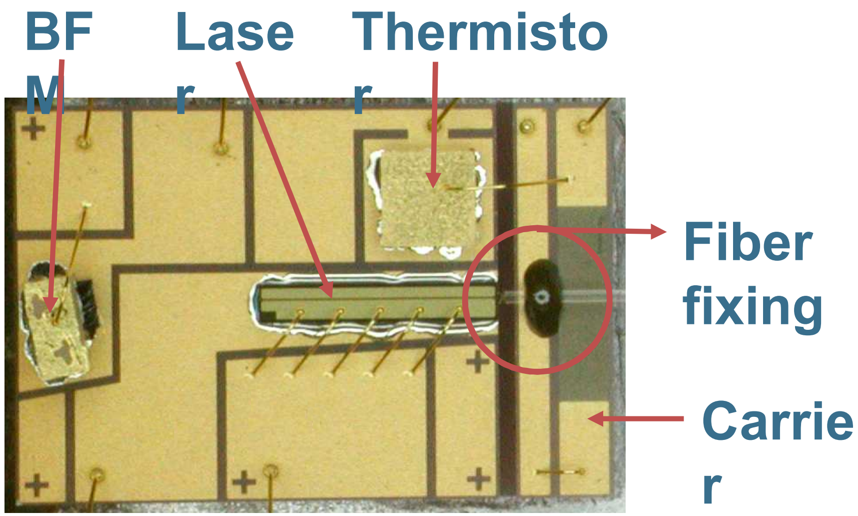
- 600 mW Power at 1 A operating current
- Wavelength locked by FBG over 70 K with high side lobe suppression ratio

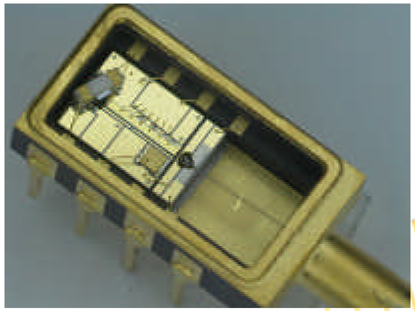


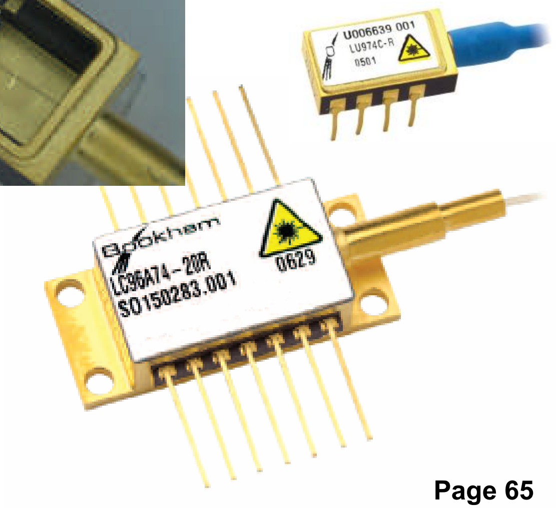


Single Mode Fiber Pump Module

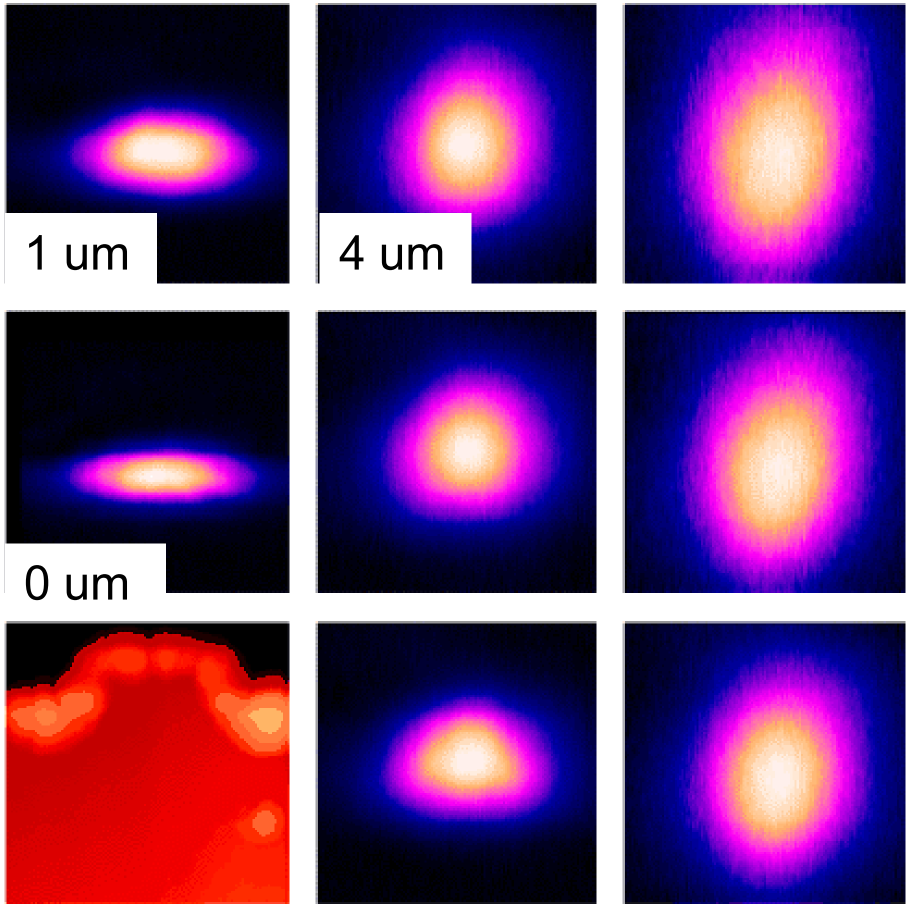
- Fully monolithic planar AlN substrate
  - Extremely low mechanical creep
  - Cost effective automation
  - Excellent thermal properties
- Used in Butterfly packages and coolerless MiniDIL
  - i.e. 400 mW Submarine MiniDIL, 600mW Butterfly



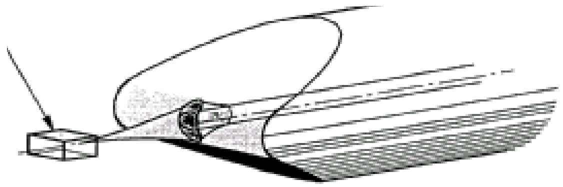




Pump Diode Beam



Prof. Unlü, Boston



Single Mode Fiber: NA=0.12

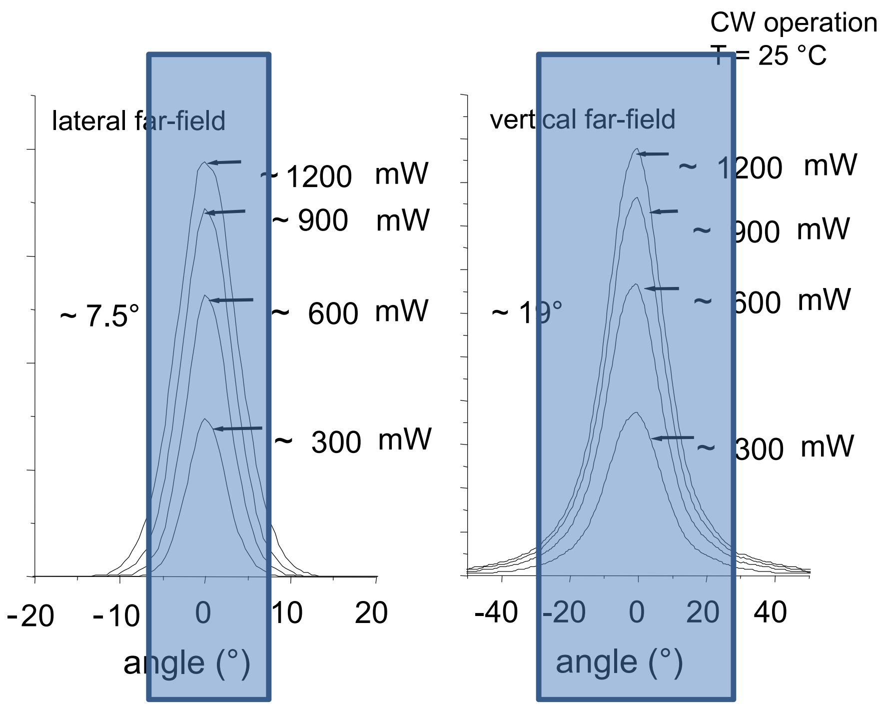
Laser Diode:

- In slow axis: NA=0.12, matched to NA of fiber
- In fast axis: NA=0.5, polish lens on fiber tip

Coupling

- At distance of 4um: Profiles match

Pump Diode Beam

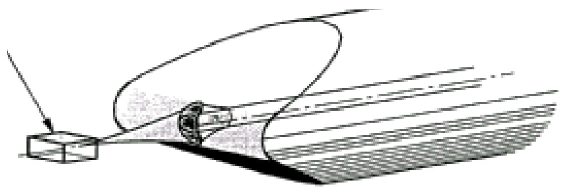


NA=0.12 NA=0.5

NA=sin(angle)~angle

Slow axis: NA=0.12 ~7deg

Fast axis: NA=0.5~30deg



Single Mode Fiber: NA=0.12

Coupling: NA matching

- Laser diode in slow axis: NA=0.12, matched to NA of fiber
- Laser diode in fast axis: NA=0.5, polish lens on fiber tip

Coupling: Amplitude matching

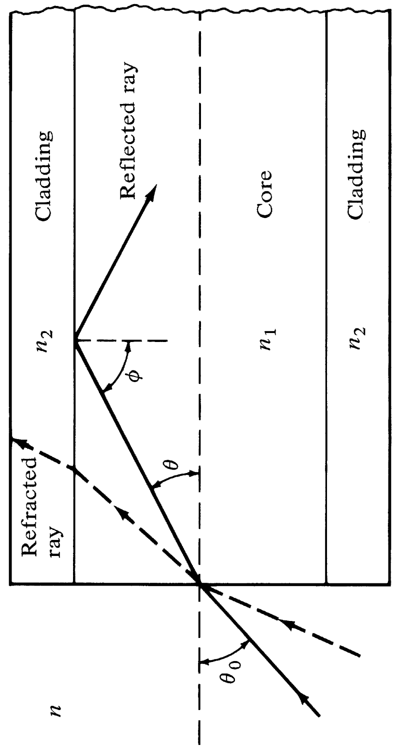
- At distance of 4um: Profiles match

Pump Diode Beam: Slow axis

Pump Diode is dielectric waveguide

- Low loss through total internal reflection
- Can be decomposed in slow axis and fast axis
- Each a dielectric slab waveguide with

$$\mathrm{NA} = n \sin\theta_{0,\max} = (n_1^2 - n_2^2)^{1/2} \approx n_1\sqrt{2\Delta}$$

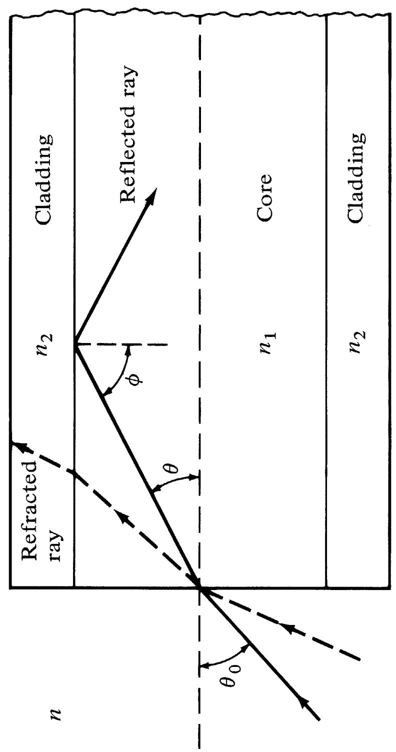


$\Delta = dn = n_1 - n_2$

$dn = 1/2*(NA/n)^2$

For NA=0.12 and n=3.6 ->**dn=5*10^{-4}**

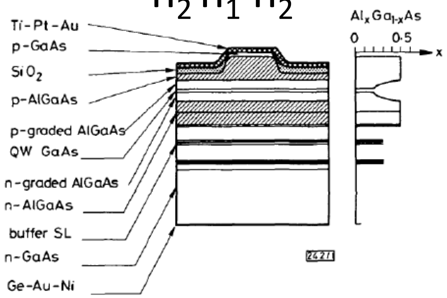
Pump Diode Beam: Slow axis



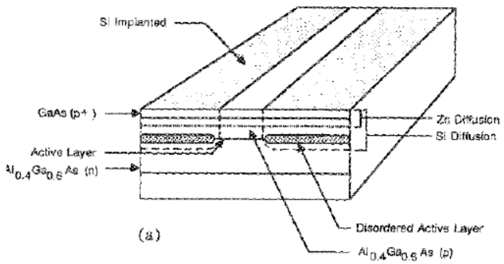
For slow axis: Need waveguide with small **dn=5*10^-4^** n

How can this be achieved?
By weak waveguide such as

n_2 n_1 n_2



n_2 n_1 n_2

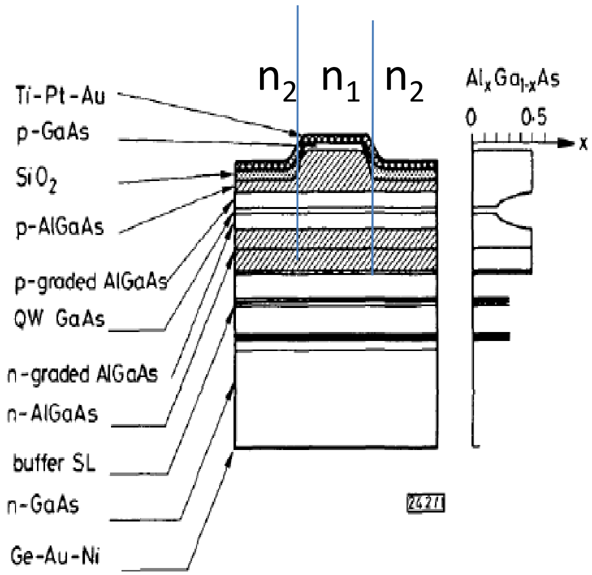


Ridge Waveguide

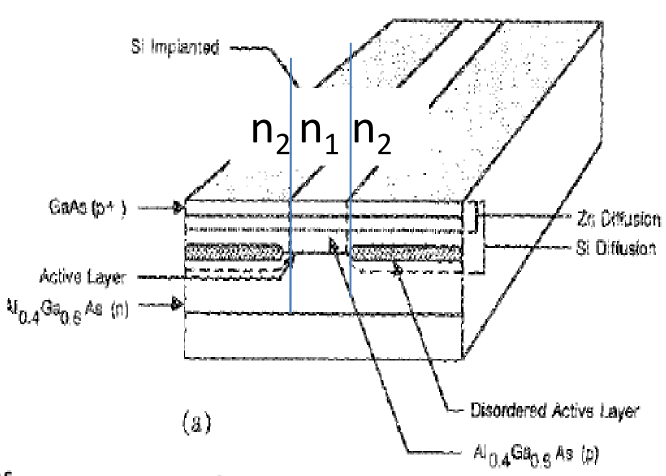
Disordered waveguide

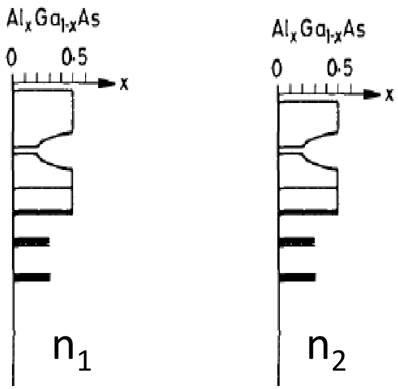
$dn=n_1-n_2$

Pump Diode Beam: Slow axis Effective Index approach



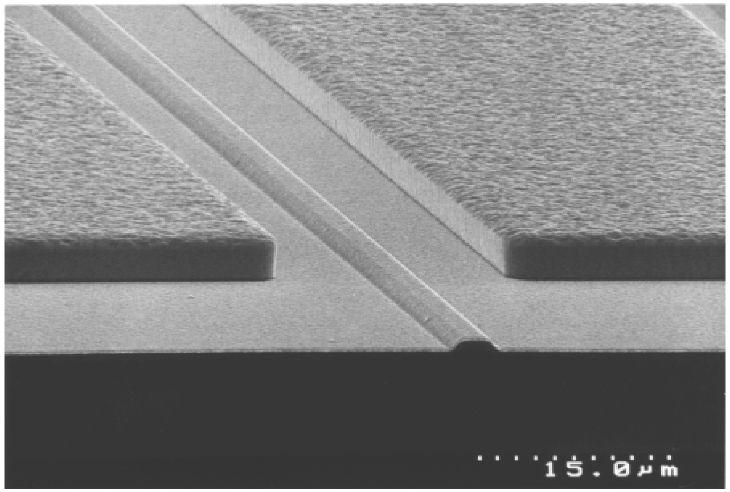
$dn=n_1-n_2$

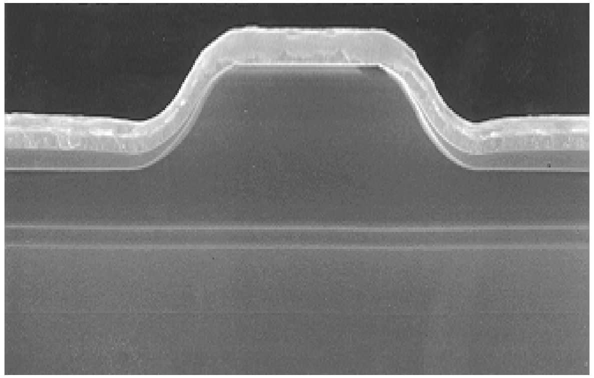




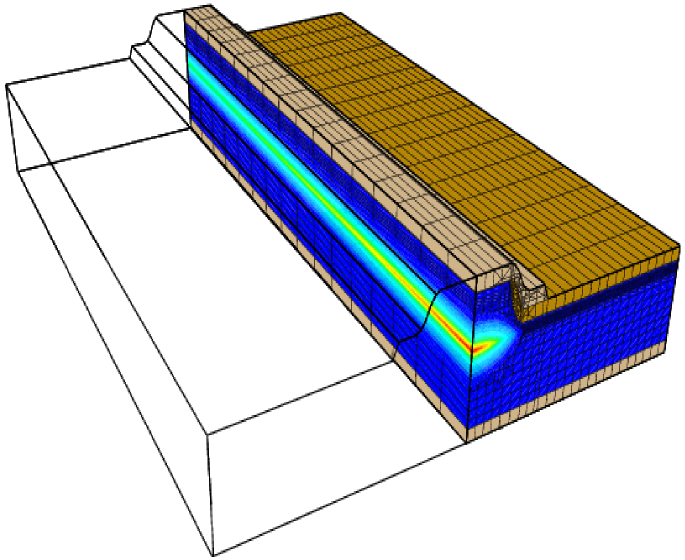
- Effective Index approach
  - Calculate effective index of planar waveguides (center and outside)

Ridge waveguide

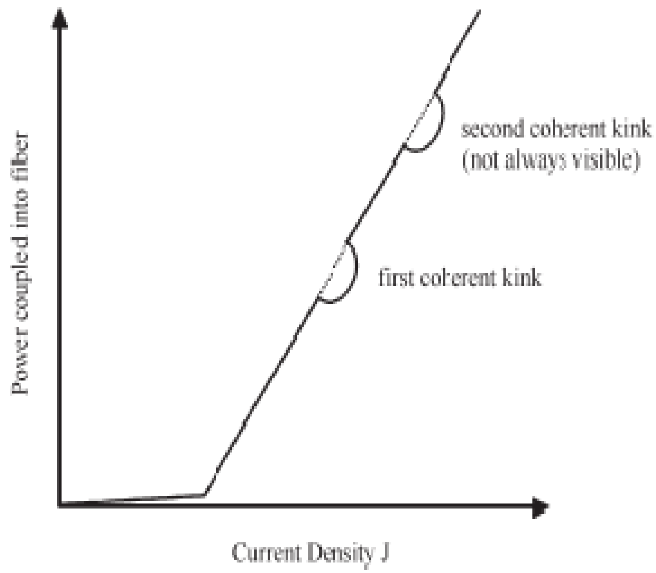


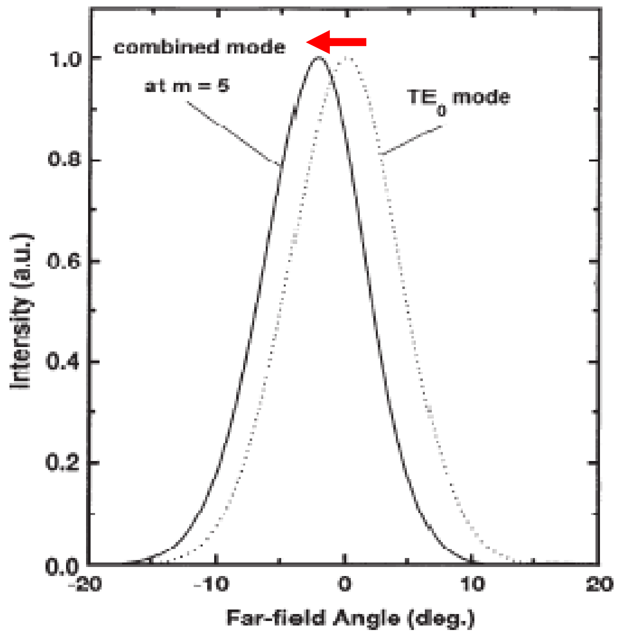


- Ridge Waveguide
  - One growth step, simple process
    - Built in reliability
    - InGaAlAs for best material properties
  - Confinement
    - Index guided mode: High linear power and excellent coupling to fiber
    - Temperature insensitive current confinement
  - Scalability
    - Increase power by making chip longer



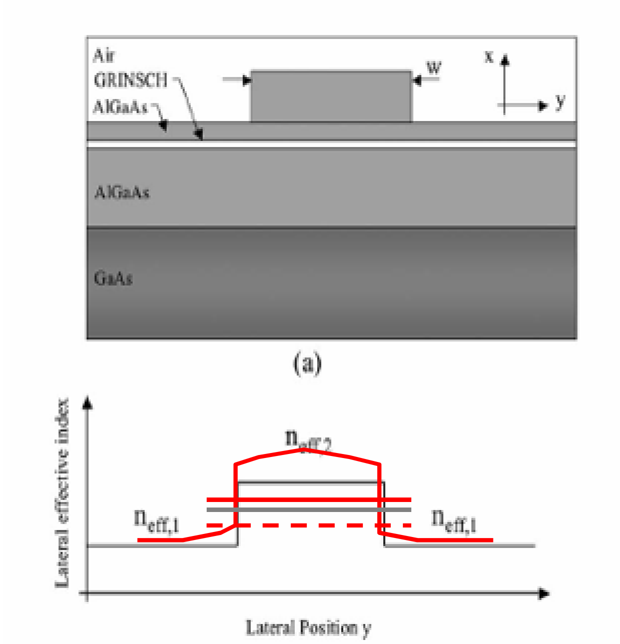
‘Shift’ Kink: Observation

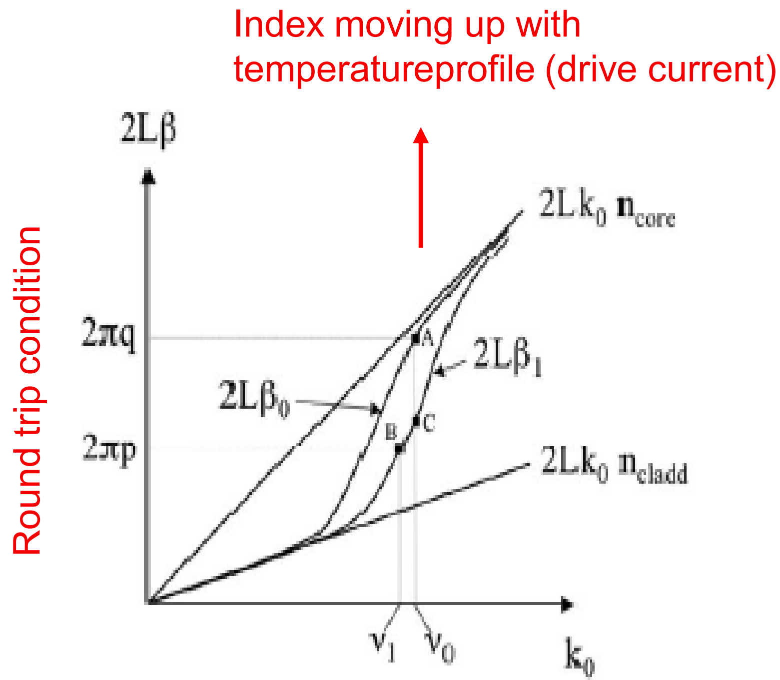




- Observation (1991)
  - Sudden kinks in fiber coupled power
- Farfield observation
  - Still single ‘humped’, but shifted during kink. Still single mode? (no!)
- Standard countermeasure:
  - Increasing loss for higher order modes (to keep them below threshold): Does not work

Shift Kink: Lateral Mode Locking



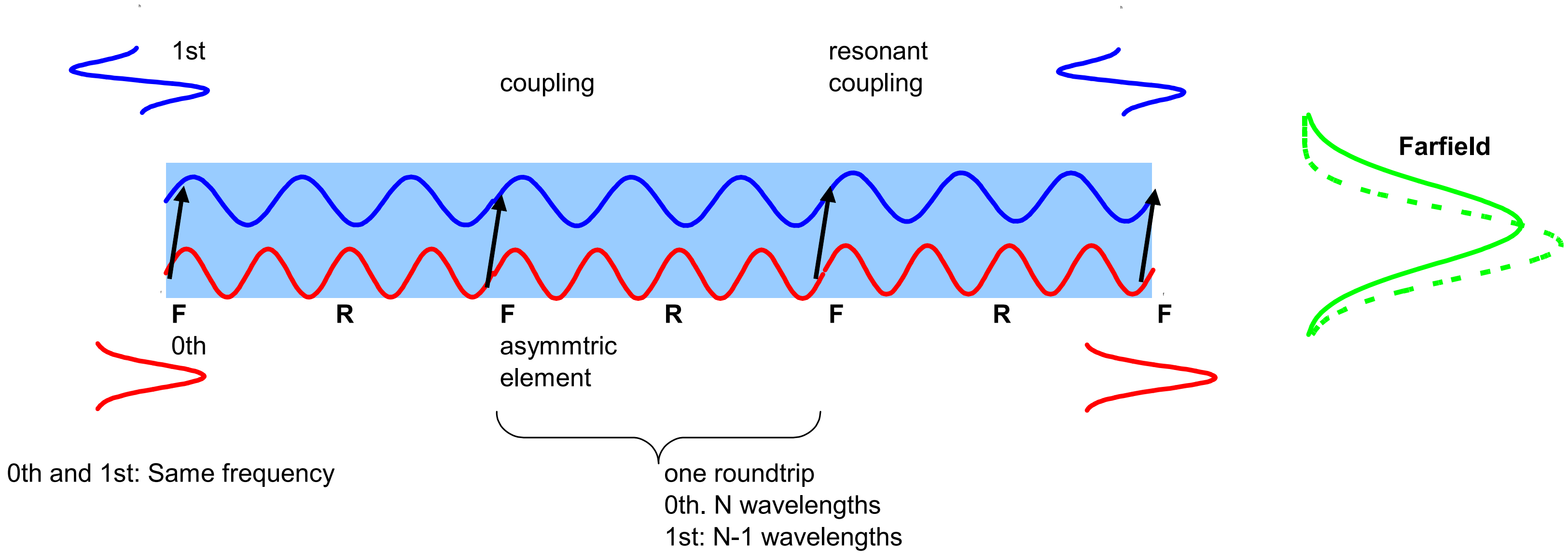


For $\upsilon_1 = \upsilon_0$

Coherent coupling

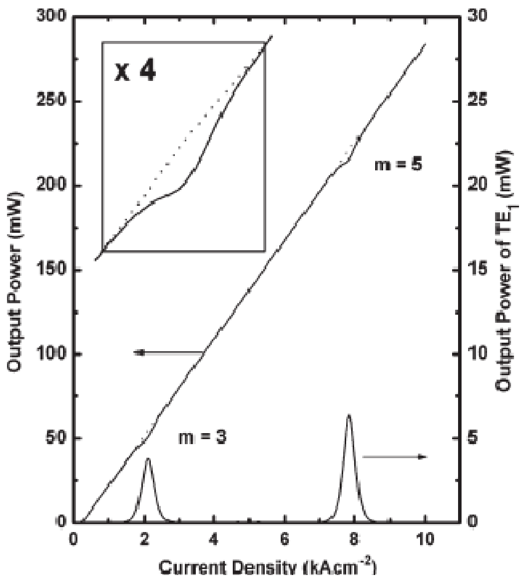
- Waveguide
  - Index increases with local heating
  - Waveguide becomes multimode
- Dispersion characteristics of waveguide
  - Phase lasing condition (integer number of wavelengths in one roundtrip) can be meet for one frequency ($\upsilon_0 = \upsilon_1$) for fundamental and higher order modes at the same time

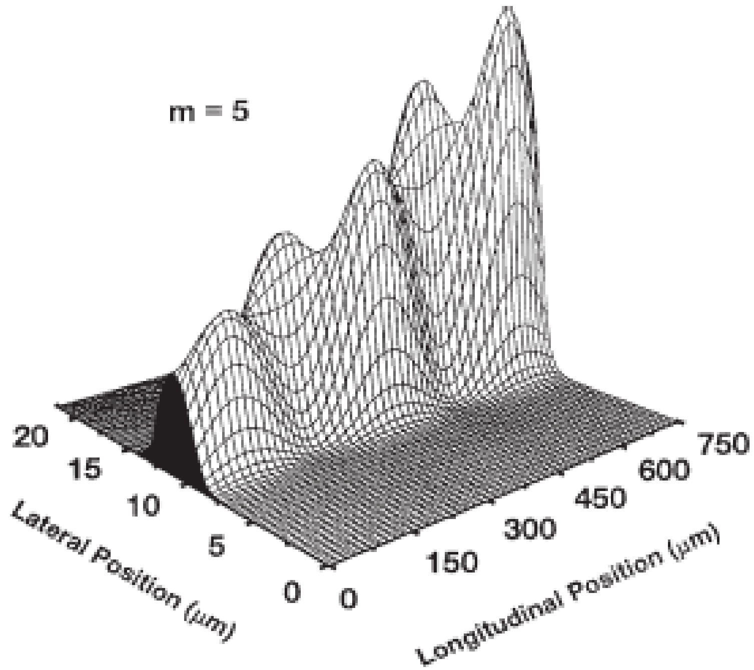
Shift Kink: Coherent Coupling



- Small asymmetry (e.g. at front mirror) couples power from fundamental to higher order mode
- Phasematch condition given at special dispersion point (temperatureprofile, i.e. drive current):
  - 'lateral mode locking' at this current > Coherent Supermode

Shift Kink: Lateral Mode Locking





Coherent Supermode:

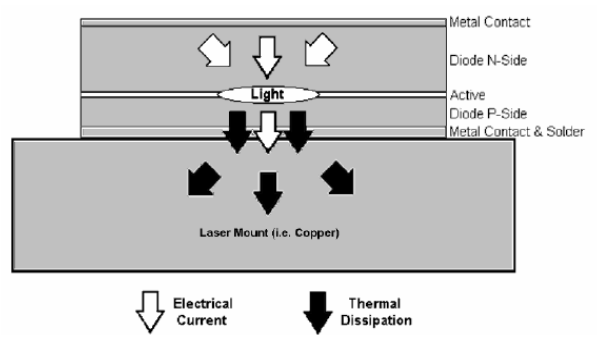
Introduction of loss for higher order modes just reduces overall efficiency

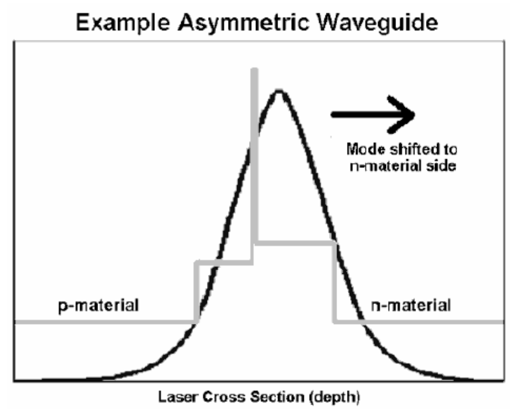
Interference within waveguide

Achtenhagen, Hardy and Harder, JQE Vol24 pp2225

Epitaxial structure

- Fast axis NA:
  - As long as NA<=0.5: No concern
- Of concern
  - High efficiency
  - Low loss, low series resistance
  - Controlled, low overlap with gain, low gamma





Epitaxial Structure

$$\boxed{\frac{P_{out}}{I \cdot V} = \eta_I \cdot \eta_V \cdot \eta_P}$$

$$\eta_I = 1 - \frac{I_{th}}{I} - \frac{I_{leak}}{I}$$

Bandgap discontinuities
Thermal and vertical leakage
Injection barriers

$$\eta_V = 1 - \left(\frac{1}{eV}\right) \cdot \left(\Delta E_f - h \cdot \nu\right) - \left(\frac{1}{eV}\right) \cdot \left(\underbrace{\Delta E_{\delta Fh} + \Delta E_{\delta Fe}}\right) - \left(\frac{I}{V}\right) \cdot \left(\underbrace{R_{sh} + R_{se}}\right)$$

$$\eta_P = \frac{1}{1 + S_f + \dfrac{\ln(R_b)}{\ln(R_f)} + 2 \cdot \dfrac{\alpha L}{\ln(R_f)}}$$

Resitivity:
Series resistance
Density of States:
Free carrier absorption

Material limits: Even after optimized mirror losses (S_f, R_f, R_b) and low threshold current.

- Due to limited mobility and carrier mass there are always trade-offs in
  - doping levels (series resistance R_s vs free carrier absorption) and
  - Bandgap discontinuities (leakage losses vs injection barriers)

Today's approach:

- InGaAlAs material system, Electrons with low mass
- Asymmetric (thin p-region), low aluminum, low confinement LOC, low doping levels
  - Electrons have low mass (high mobility and low density of states).
- Relatively low barriers for high mobility and good injection (some thermal and vertical leakage)

Epitaxial Structure

Bandgap design to optimize

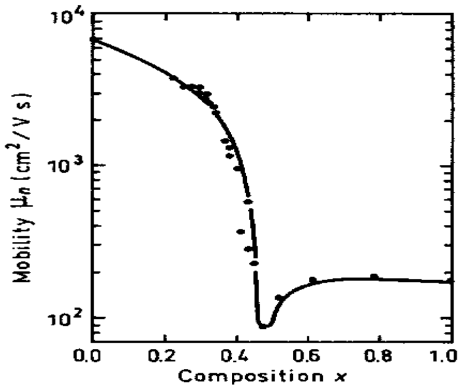
Bandgap discontinuities
Thermal and vertical leakage
Injection barriers

Doping design to optimize

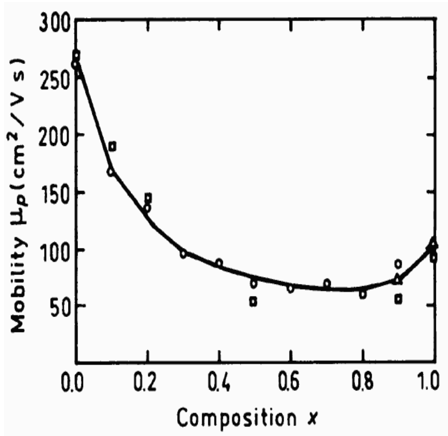
Resitivity:
Series resistance
Density of States:
Free carrier absorption

Highly asymmetric physical parameters:

Electron mobility:



hole mobility



Free carrier absorption: $\alpha_p = 7 - 14{\cdot}10^{-18}p$ $\alpha_n = 3 - 6{\cdot}10^{-18}n$

-> Use asymmetric epitaxial structure

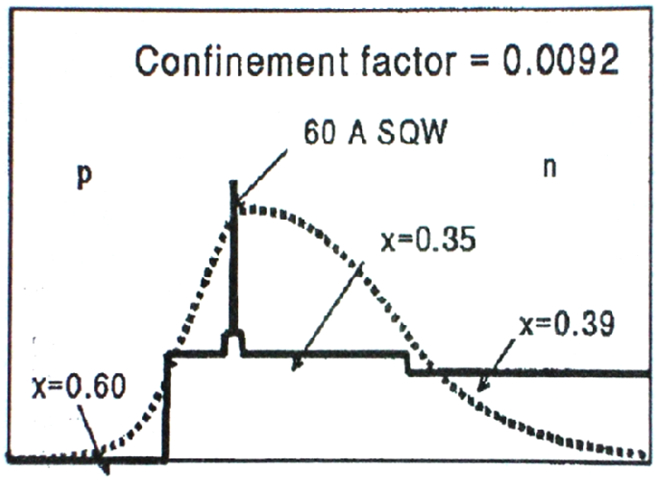
Epitaxial Structure

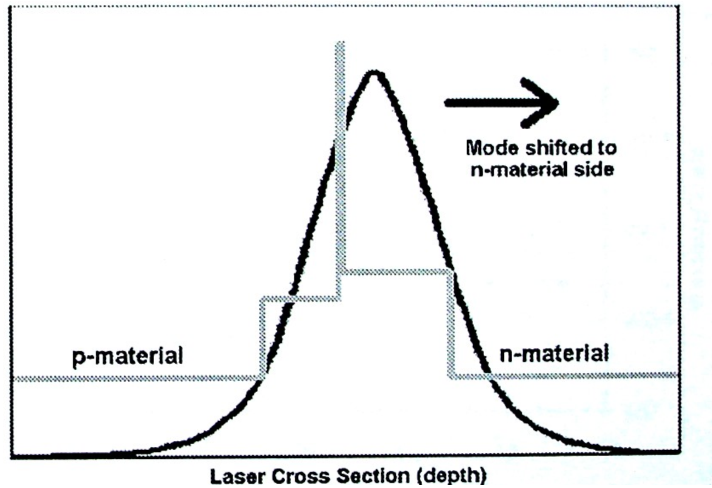
Asymmetric waveguides

Mode maximum shifted from the QW position: lower FC absorption in QW
Values of a_{FC} as low as 0.4 cm^{-1} were reported

Free carrier absorption in *p* material is higher than in *n* material:
- higher absorption cross section;
- higher doping for comparable conductivity required;

=> The design idea is to shift optical mode from *p*- to *n-type* material



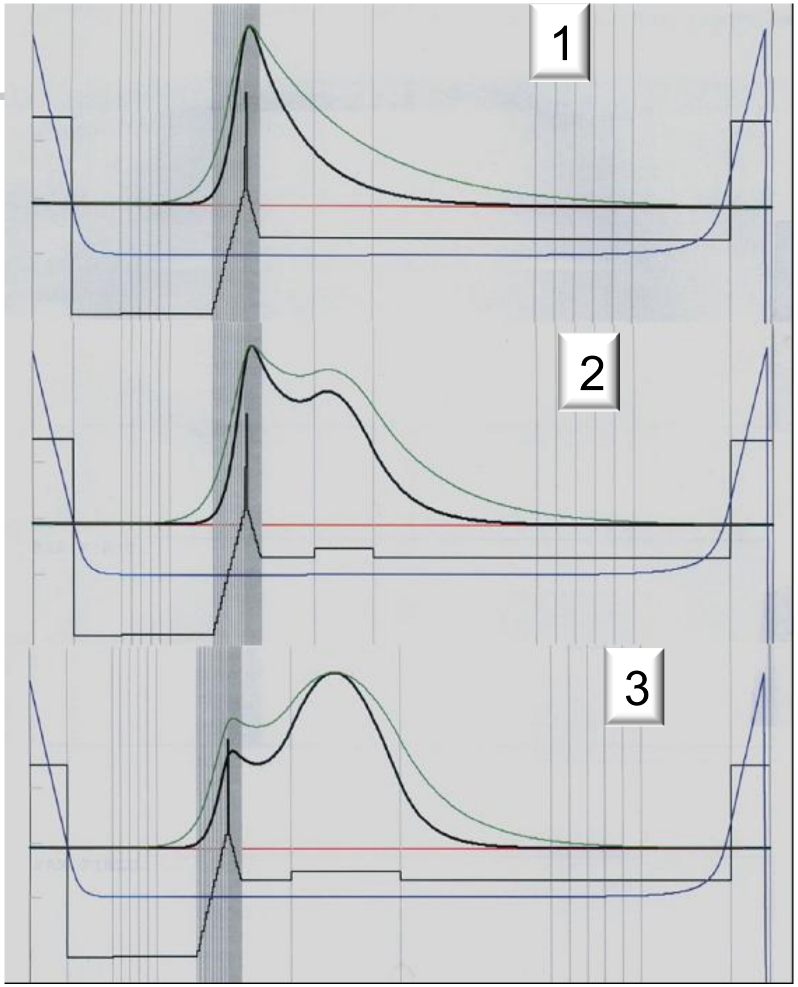


In addition higher order modes can be suppressed

M. Buda *et al., JSTQE*, v.3, p.173 (1997)   C.M. Stikley *et al., SPIE Proc.*, v.6104, (2006)

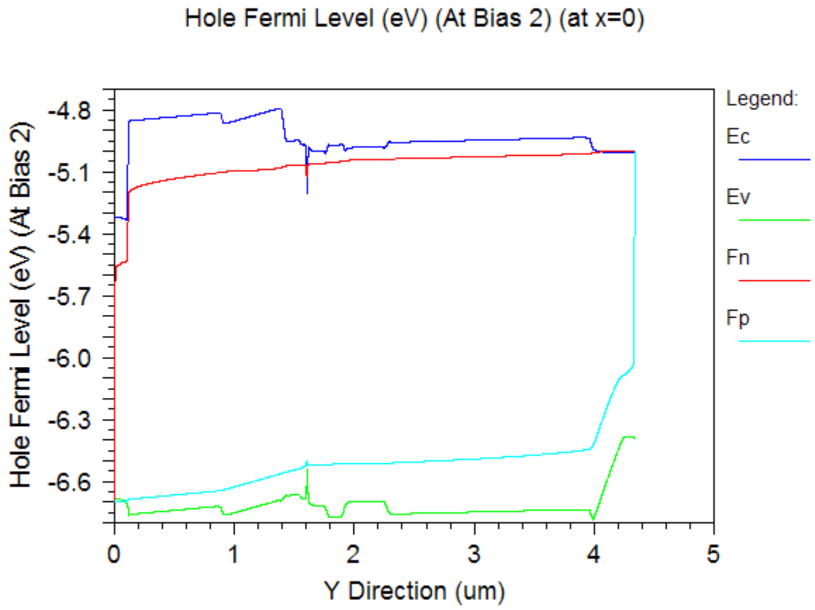
Epi structures with low Γ

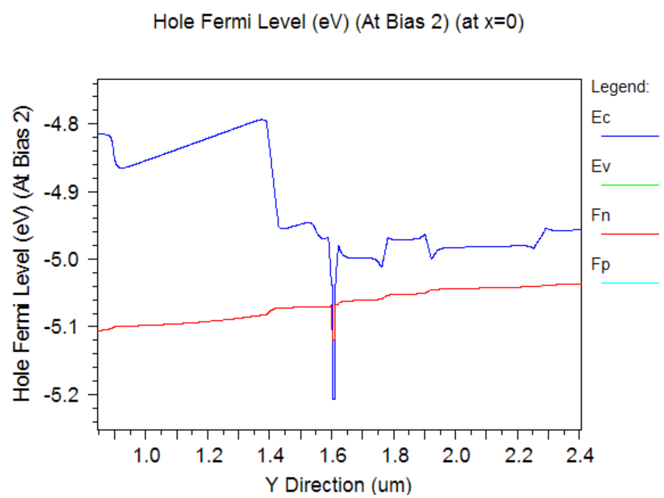
- Asymmetric, with optical trap on n side
- 1.7 times decrease in Γ (from 1 to 2) by using the trap
- Γ is changed by only changing the trap width (2 & 3) – easy execution
- Advantages:
    - Lower attenuation coefficient
    - Lower thermal resistance
    - Narrow FF

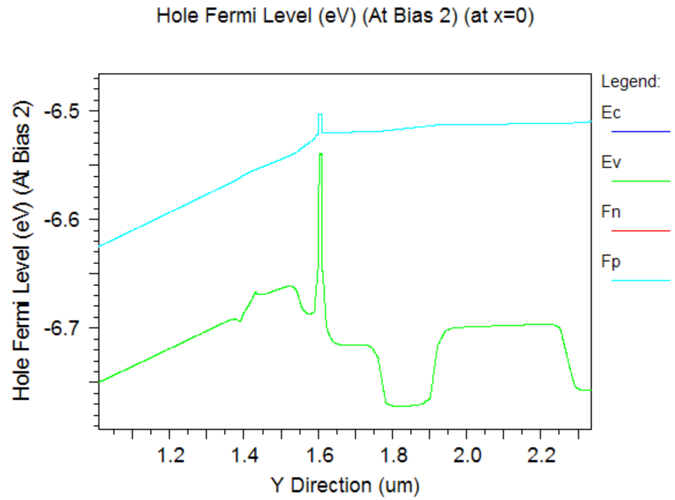


Dr. Julian Petrescu-Prahova

Epitaxial structures (Rsoft)



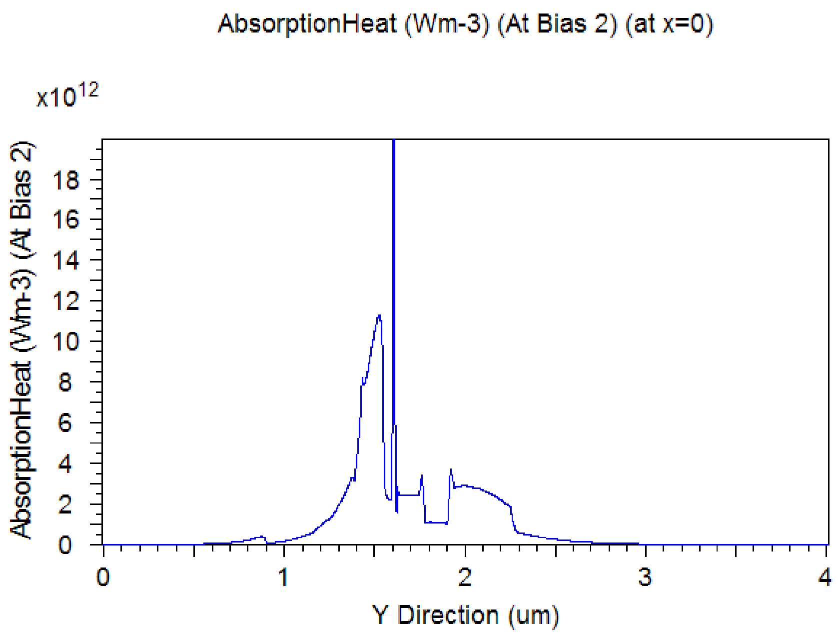


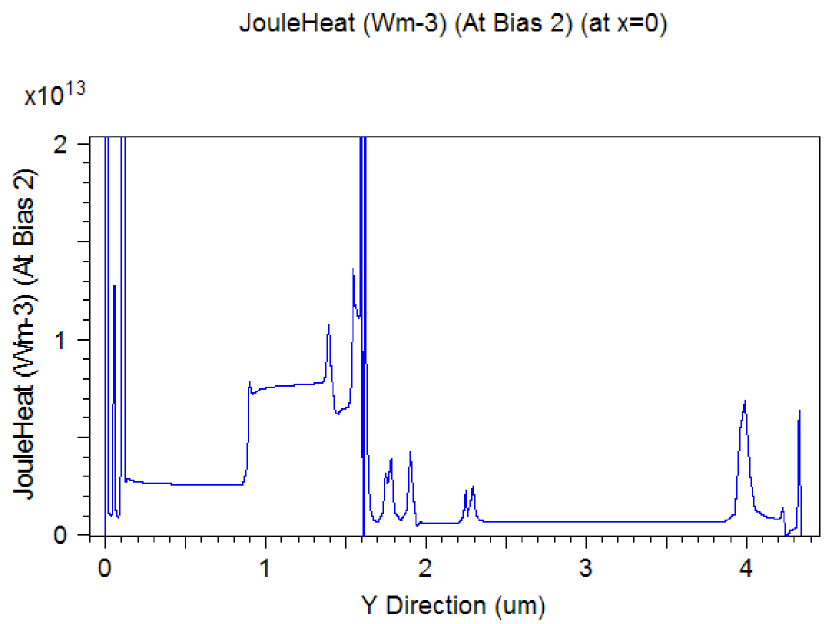


- At 5kA/cm2

(calculated with Mode from Rsoft)

Epitaxial structures (Rsoft)

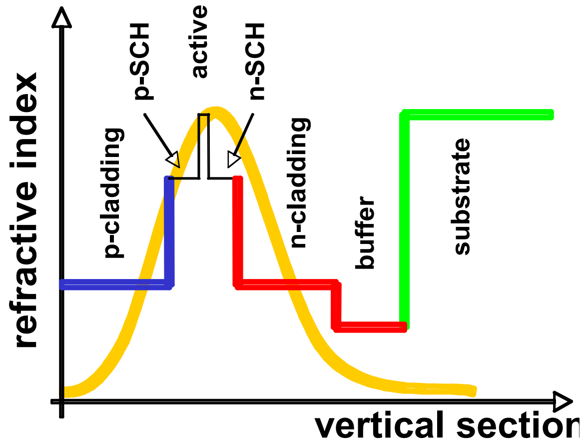




- Free carrier absorption

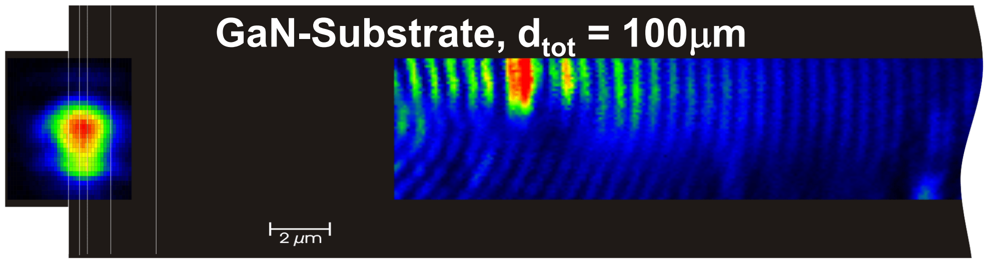
Joule heating

Optical Waveguide & Substrate modes: GaN* laser diode

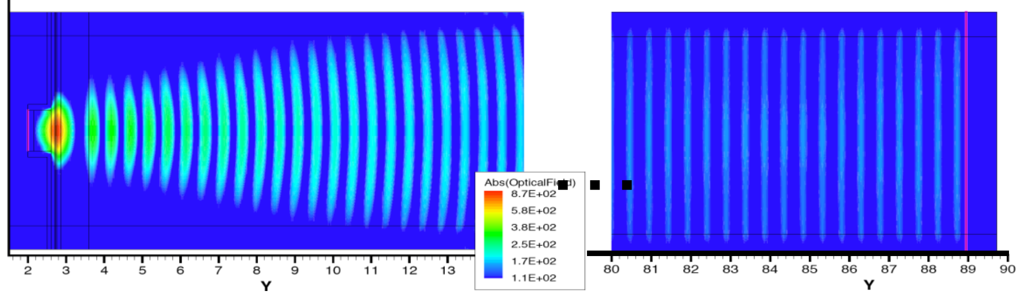


	GaN	SiC	Al2O3
Strain %	0.0	3.4	16
Refr. Index	2.52	2.75	1.78

SNOM



Simulation



Potential Impact of Substrate Modes:

- optical loss
- gain oscillations

*Source: Prof. B. Witzigmann et al., IEEE JQE 2007

Length Scaling

Length Scaling

- Increase power: Have to make laser longer to better remove the heat.
- Most important laser parameters:
  - Gain(G), efficincy(η), photon lifetime (τph), internal power ratio (Pr)
    - as function of absorption(α), lenght(L), confinemnet (Γ), front mirror refelctivity R (for backmirrror reflectivity=1.

$$G = \left(\alpha + \frac{1}{2L} * \ln\left(\frac{1}{R}\right)\right)/\Gamma\ , \quad \eta = \left(\frac{1}{2L} * \ln\left(\frac{1}{R}\right)\right)/\left(\alpha + \frac{1}{2L} * \ln\left(\frac{1}{R}\right)\right)$$

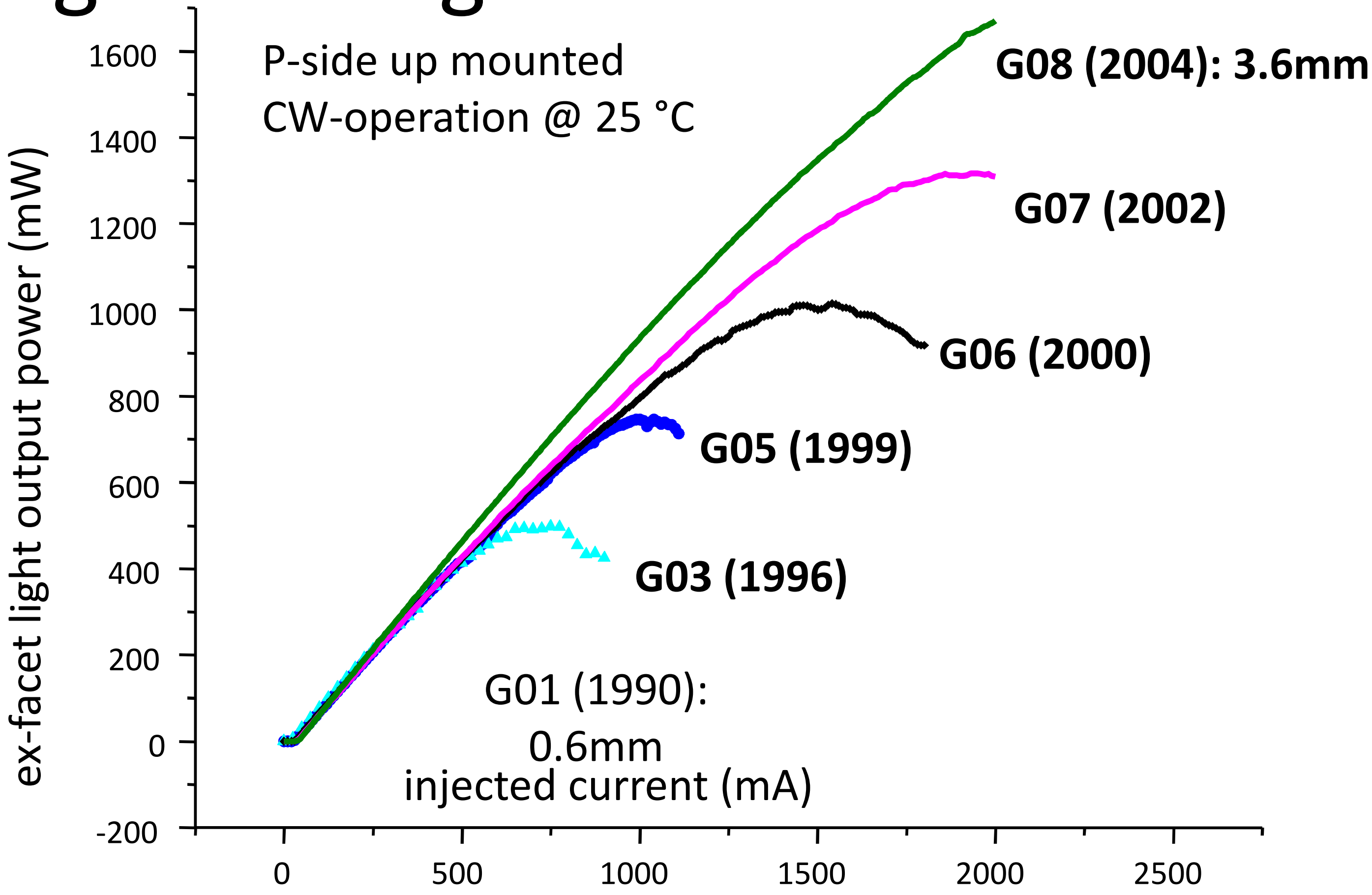
$$\tau_{ph} = 1/\left(v_{gr} * \left(\alpha + \frac{1}{2L} * \ln\left(\frac{1}{R}\right)\right)\right), \quad Pr = (1+R)/(2 * \sqrt{R})$$

- Keep Gain(G), efficincy(η), and internal power ratio (Pr) constant
  - Scaling rule for R, Γ and α for lasers with length L

$$R(L) = R(L_0) \quad \Gamma(L) = \frac{L_0}{L} * \Gamma(L_0), \quad \alpha(L) = \frac{L_0}{L} * \alpha(L_0)$$

- **Output power scales then linearily with length L (at const current density)**
  - i.e. For 4mm long chip: R=0.03, α =0.8cm $^{-1}$ and Γ=1% (η=85%),
  - for 8mm long chip: R=0.03, α =0.4cm $^{-1}$ and Γ=0.5% (η=85%)
  - > Need low loss and low confinement structures

980nm Single Mode Pump Diode: Length Scaling

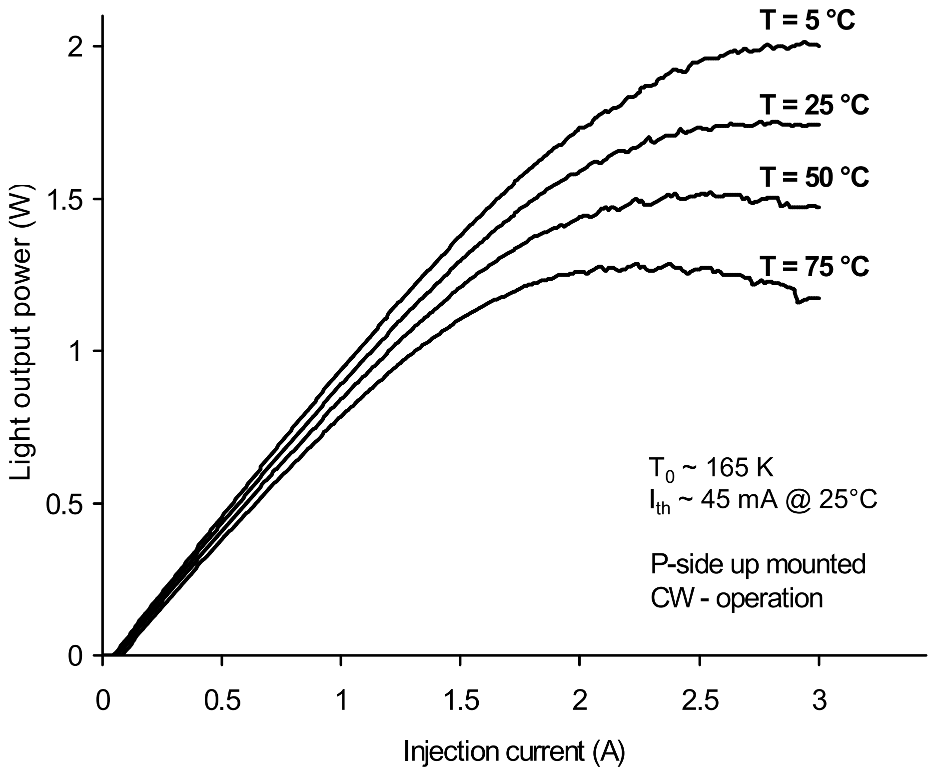


Improve performance by making laser chip longer

1. Low loss waveguide
2. Need facets which can sustain high powers

Courtesy Bookham

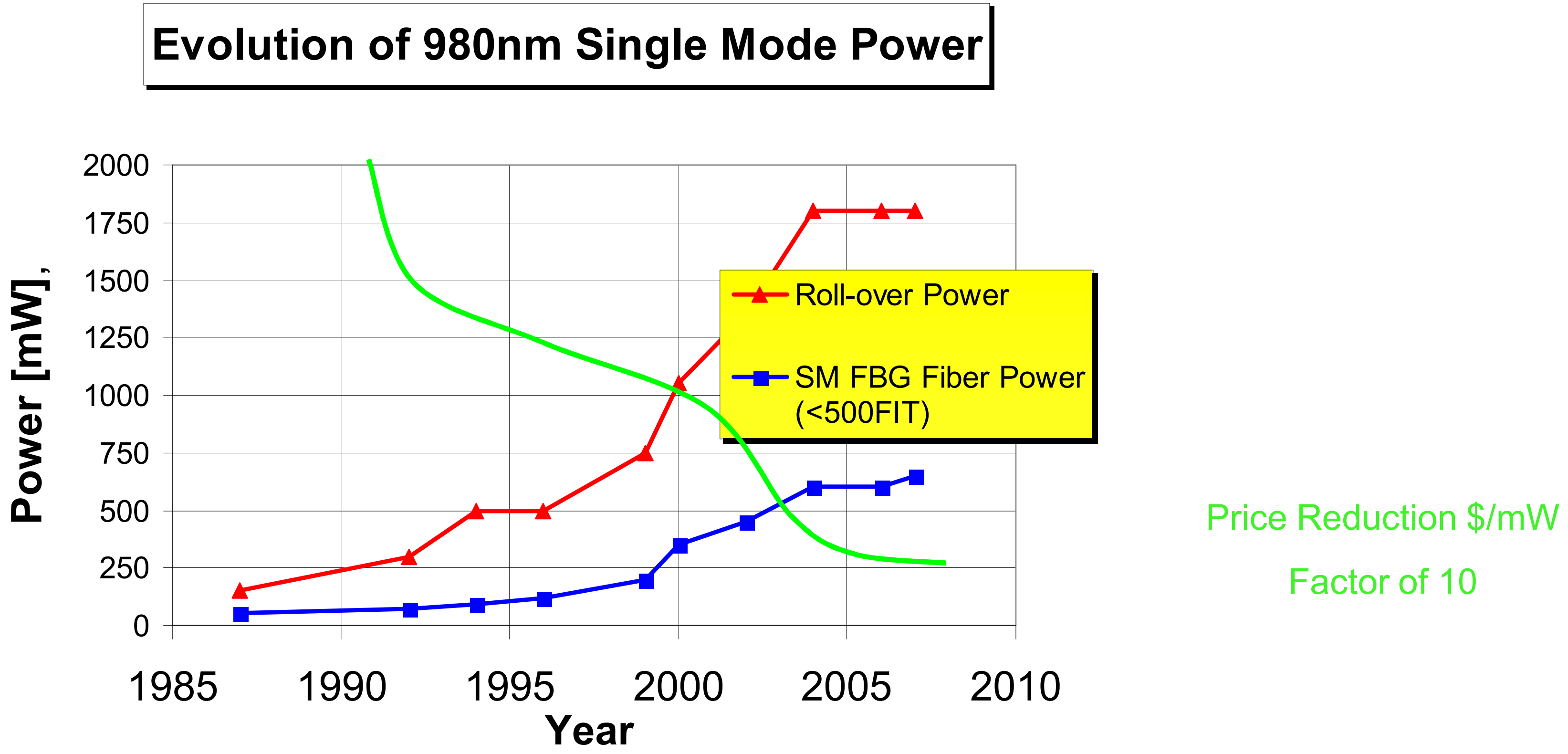
980nm single mode pump chip: 2004



150MW/cm2

- Reliability
  - Better than 500FIT (0.5%/year) at Pop=850mW
- Wallplug Efficiency
  - >60% peak, >50% up to 800mW
- Beam
  - Single lateral mode beyond 1200mW, shift kink: solved
  - Emission spot: 0.7um*2um

980nm Single Mode Pump Diode: Evolution



980nm Pump Diode Lasers: Matured

-> Power has reached plateau at 600mW .. 650mW

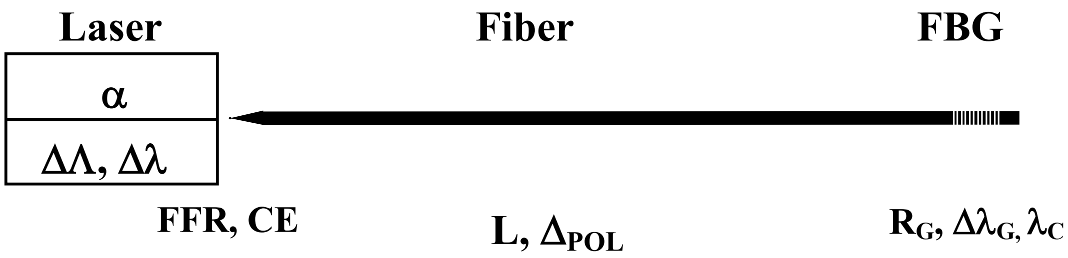
-> Cost reduction done: Assembly in China, One platfrom for various devices

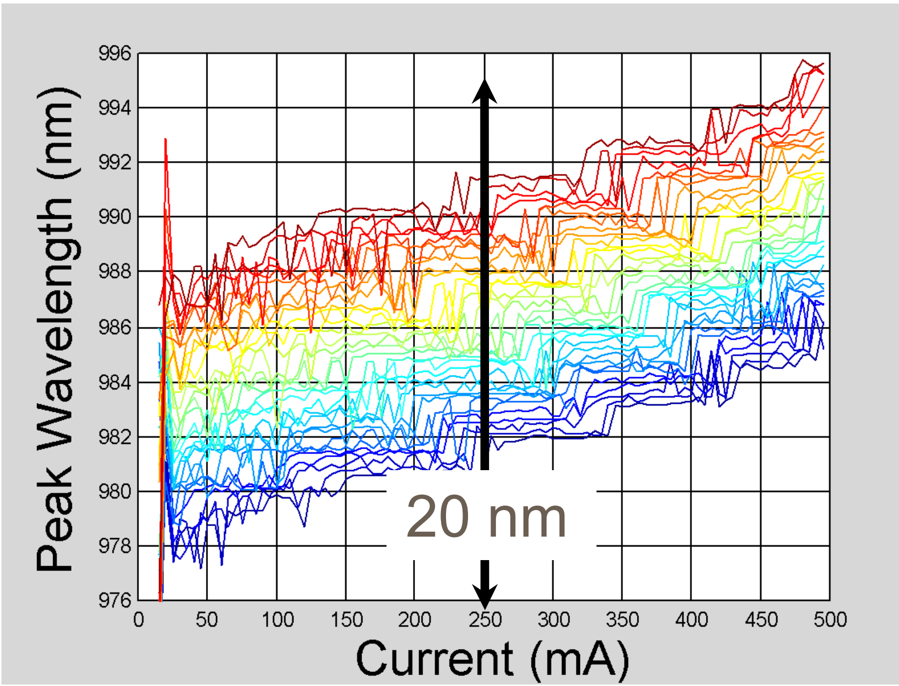
-> Spectral stability and noise: Done

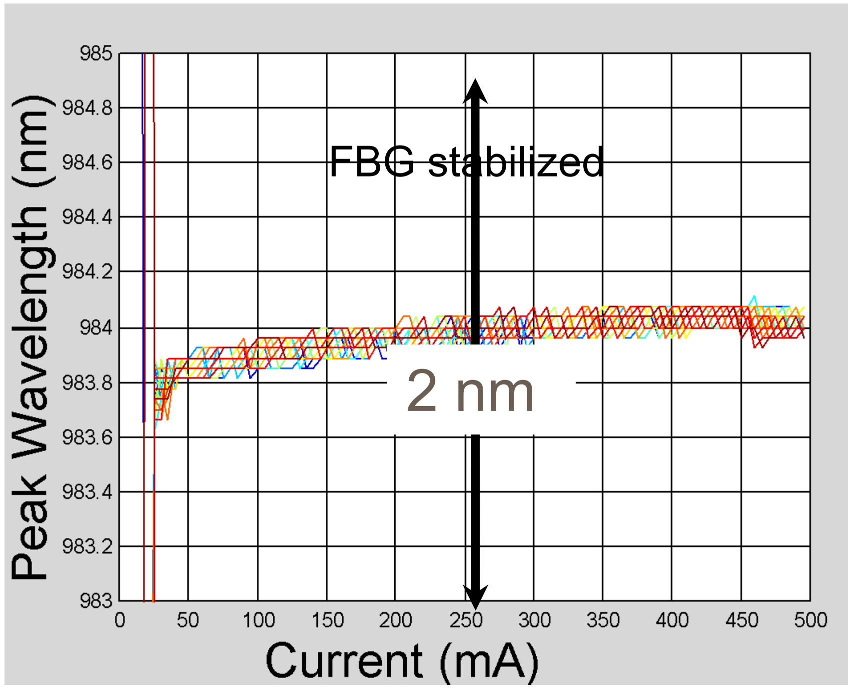
-> High efficiency: Done (Uncooled MiniDIL)

Spectral stability

Wavelength stability

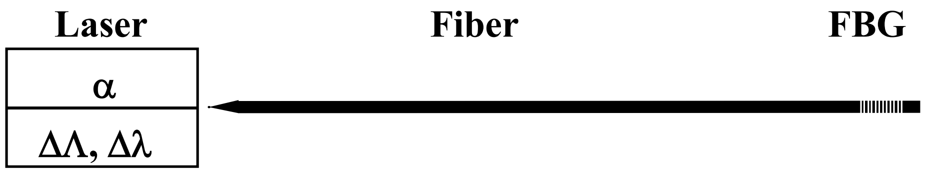


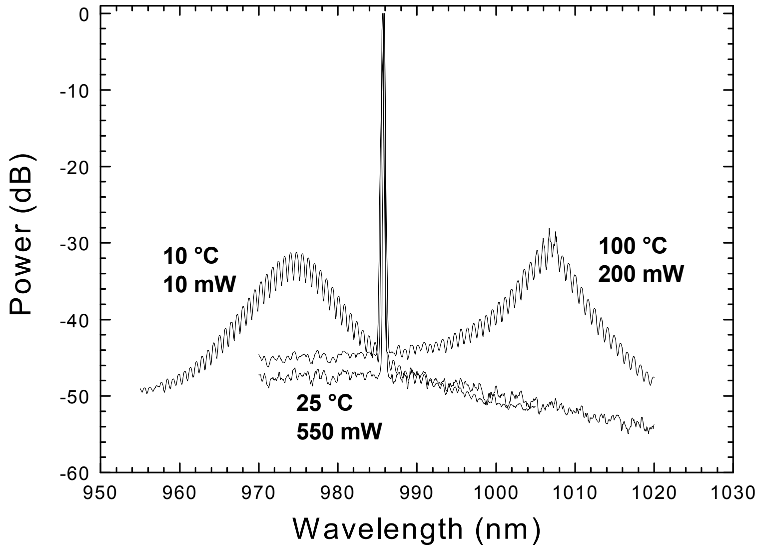




17nm Free Running Wavelength Shift
for 25mA - 500mA & 10°C - 40°C
=> 0.33nm/°C and 0.015nm/mA

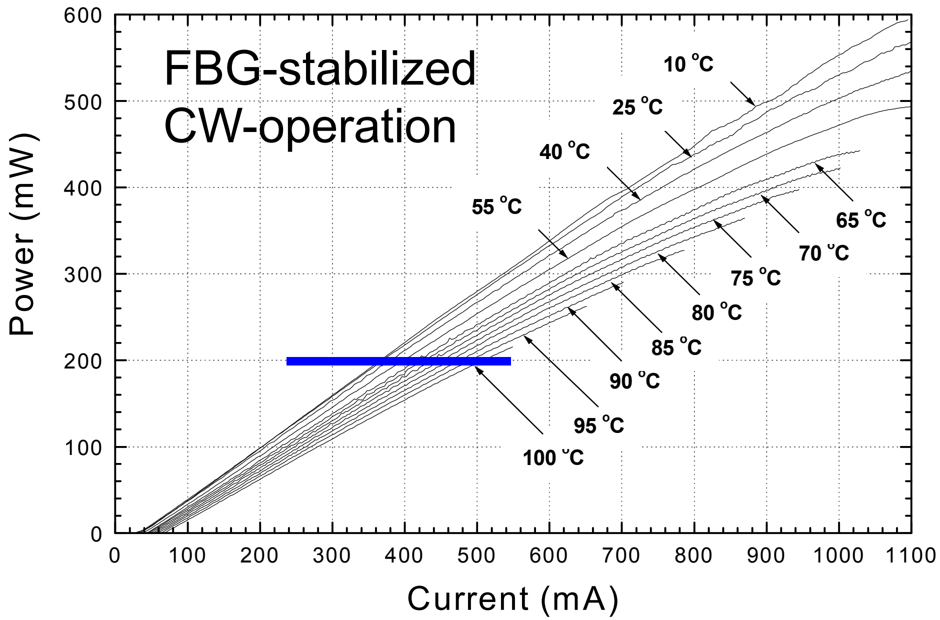
Wavelength Stability with FBG





- External fiber Bragg grating to lock wavelength

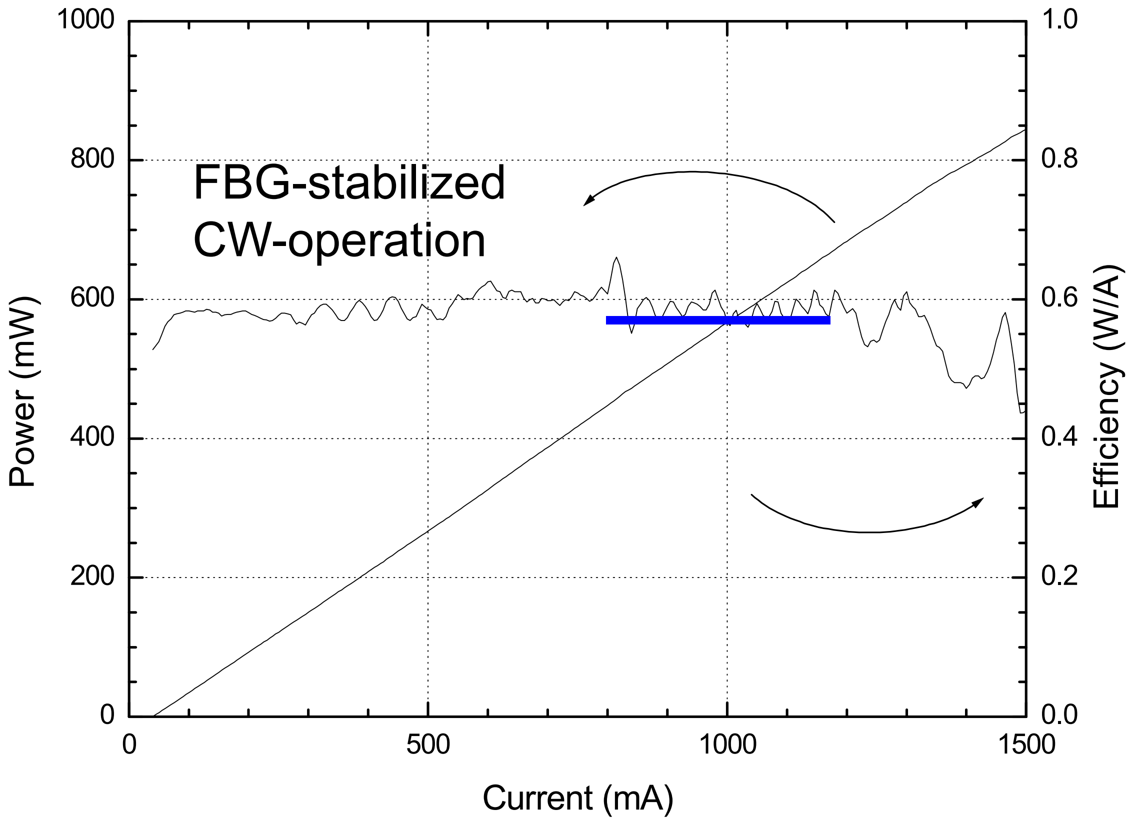
200mW G08 based un-cooled MiniDil

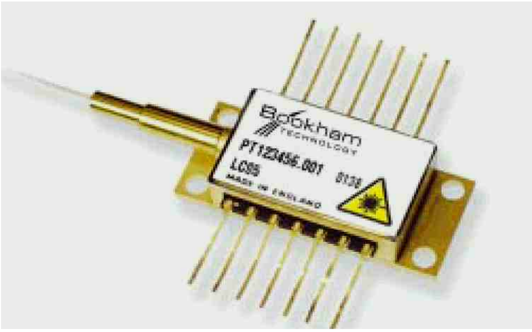


600 mW @ 10°C
400 mW @ 70°C
200 mW @ 100°C

- FBG stabilized within 1.2 nm wavelength shift from 10 °C..100 °C, 5 mW .. 200 mW
- Total power dissipation @ 200 mW in fiber, 70°C: 0.52 W
- Power variation is lower than 0.15db (50kHz bandwidth)

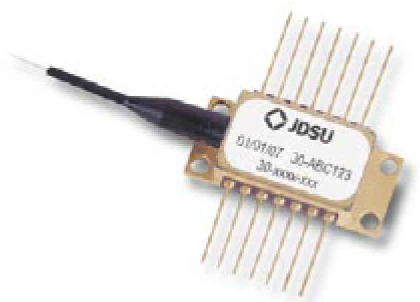
600mW G08 based pump module

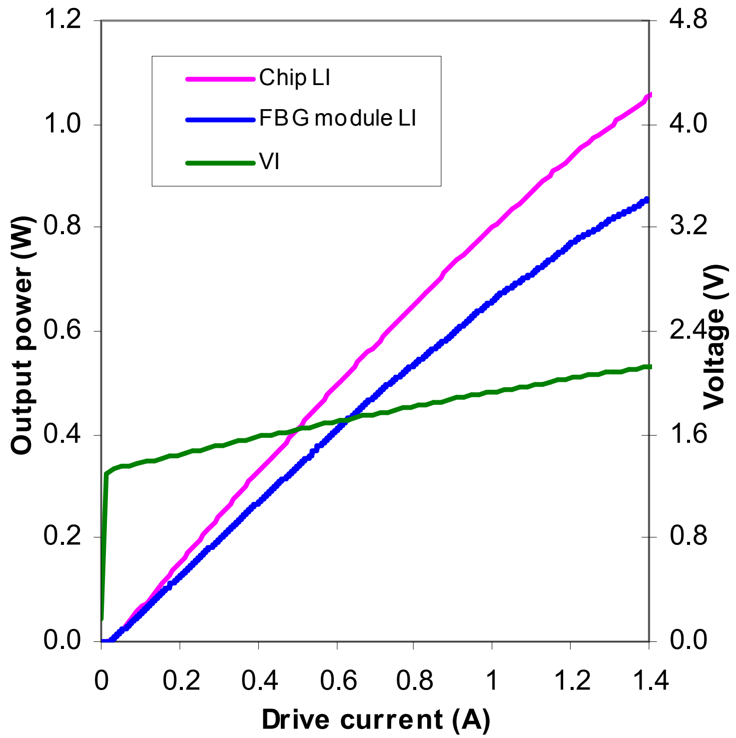


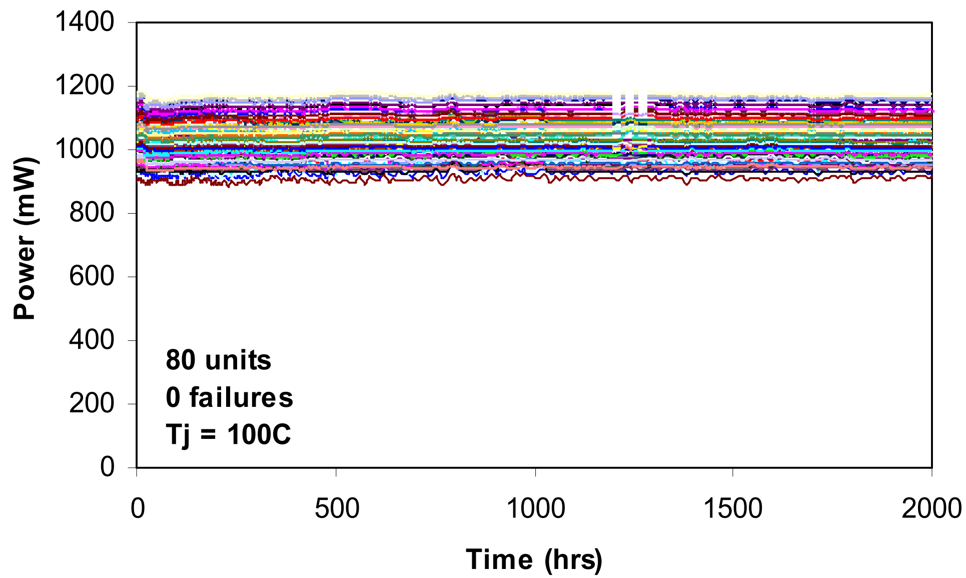


- Light output power
  - maximum module light output power ~850mW
  - fully FBG – stabilized, low noise (<0.1dB)
  - no kink issue up to 1.5A
- Operation regime
  - mainly determined by 980nm pump reliability
- Module efficiency around ~0.7 W/A in average

JDSU 980nm Single Spatial Mode Pump







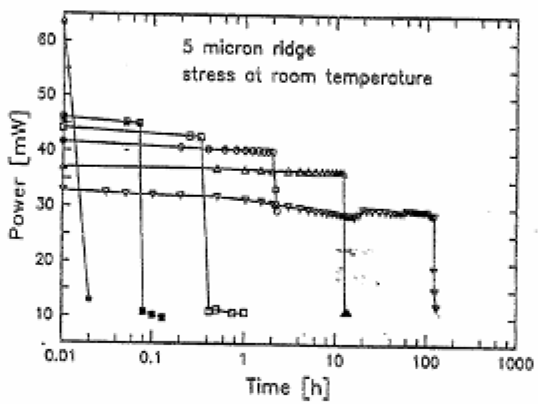
- New FBG-stabilized pump module
  - 660mW kink-free power
  - 45 FIT chip reliability at 830mW
- Mature package platform
  - 5 billion field hours
  - 5 FIT field reliability

Passivation

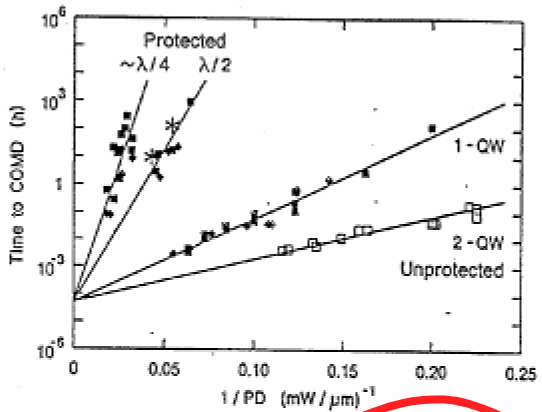
980nm Single Mode Pump Diode: Time to COMD

Mirror Passivation

Time to COMD



Arrhenius Plot



$$t_{COMD} \propto \exp\left(\frac{E_A/k}{T_M}\right)$$

$$T_M = c \times \text{Power density}$$

Chemist fixed problem

Solved in 1987 (E2)

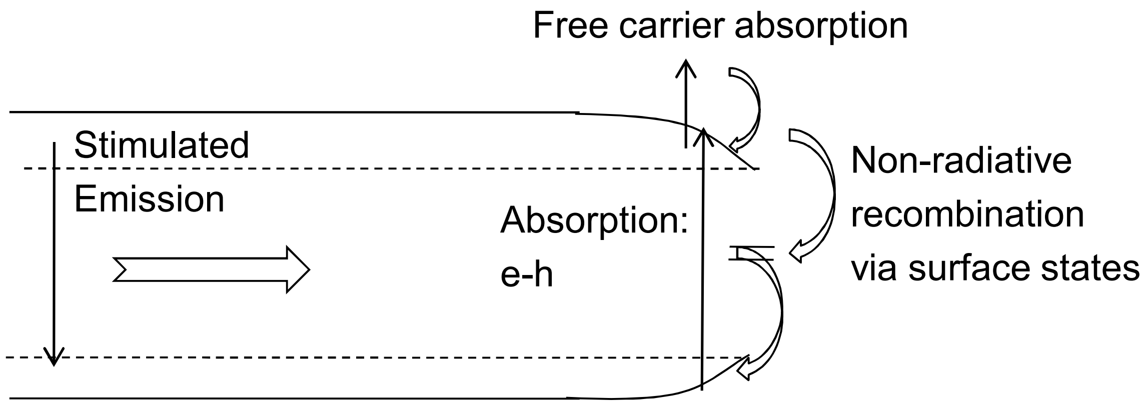
OSA_91

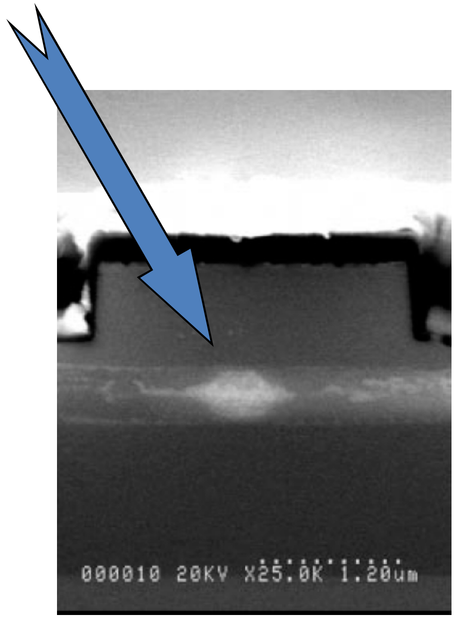
IBM

11/91 (Ch. Harder)

Long term reliability & COMD protection

Catastrophic Optical Mirror Damage (COMD)





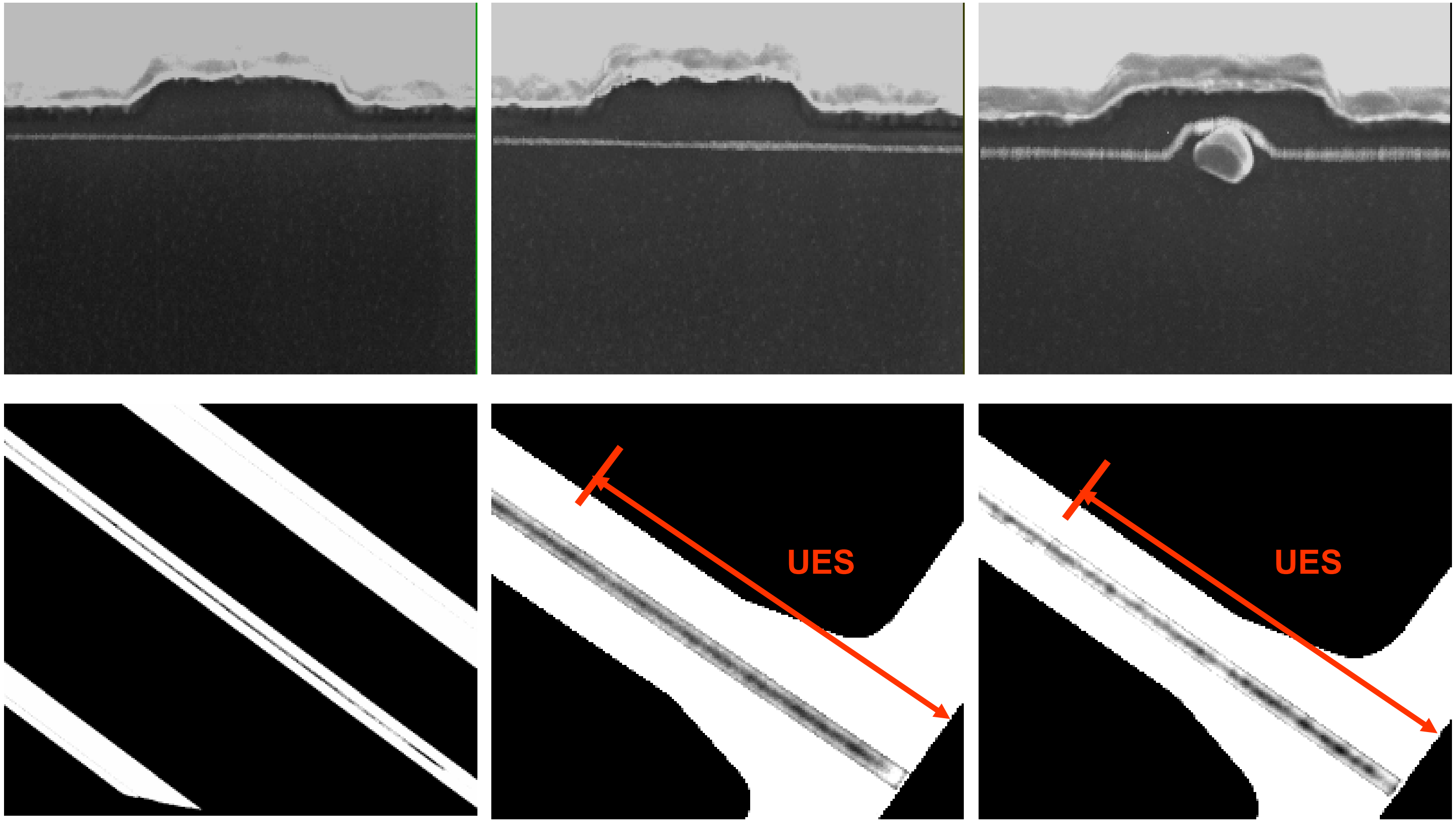
- Facet Degradation leads to formation surface states
- Surface states cause non-radiative recombination
- Non-radiative recombination leads to a local increase of current injection
- This leads to an increase of the local temperature
- Which causes a further shrinkage of the bandgap and thus
  an increase of free carriers (increased free carrier absorbtion)
- Additional generation of e-h pairs leads to further absorption
  of stimulated laser light causing an acceleration of the thermal run away .... COMD

FMA G08 : SEM / EBIC images

center bulk degradation | **front bulk degradation (without mirror damage)** | **front bulk degradation (with mirror damage)**

Front view

Top view



intense

Avoiding COMD

Avoid or reduce formation of non-radiative recombination states

- **E2 -> Cleaving in high vacuum and in-situ passivation of the cleaved surface**
- **Use of InGaAsP based barrier materials -> reduced oxidation ("Al-free") -> re-growth covering cleaved facets possible**

Remove formation of non-radiative recombination states

- **"Cleaving on air" -> Dry etching in vacuum -> in-situ nitridation or sulphation**
- **"Cleaving on air" -> low energy hydrogen plasma or ion beam cleaning -> in situ passivation (ZnSe, Si,...)**

M. Gasser, E.E. Latta, "Method for mirror passivation of semiconductor laser diodes," U.S. Patent No. 5063173 M. Hu, L.D. Kinney,

M. Pessa, et al.,"Aluminium-free 980-nm laser diodes for Er-doped optical fiber amplifiers," SPIE 1995, vol. 2397, 333-341

K. Hausler, N. Kirstaedter, "Method and device for passivation of the resonator end faces of semiconductor lasers based on III-V semiconductor material," U.S. Patent No. 7033852

L.K. Lindstrom, et al."Method to obtain contamination free laser mirrors and passivation of these," U.S. Patent No. 6812152

H. Kawanishi, et al."Semiconductor laser device with a sulfur-containing film provided between the facet and the protective film," U.S. Patent No. 5208468

E.C. Onyiriuka, M.X. Ouyang, C. E. Zah, "Passivation of semiconductor laser facets," U.S. Patent No. 6618409

P. Ressel et al. "Novel Passivation Process for the Mirror Facets of Al-Free Active-Region High-Power Semiconductor Diode Lasers," PTL 2005, vol. 17, no. 5, 962-964

Avoiding COMD

Reduce number of free carriers at the laser facet

- **Reduce direct carrier injection without changing the bandgap (at wafer level process)**

  Front section isolation

- **NAM (non absorbing mirrors) to reduce absorption, diffusion and thermalized carriers (at wafer level process)**

  Zn diffusion

  Etching and subsequent re-growth of a III-V window

  Si-doped and disordered windows

  Vacancy induced windows (QWI)

B. Schmidt et al., US Patent 6782024 - High power semiconductor laser diode

H.0. Yonezu, M. Ueno, T. Kamejima and I. Hayashi, "An AlGaAs Window Structure Laser," JQE 1979, vol. 15, no. 8, 775-781

J. Ungar, N. Bar-Chaim and I. Ury, "High-Power GaAlAs Window Lasers," EL 1986, vol. 22, no. 5, 279-280

R.L. Thornton, D.F. Welch, R.D. Burnham, T L. Paoli and P.S. Cross, "High power (2.1 W) 10-stripe AlGaAs laser arrays with Si disordered facet windows," Appl Phys Lett 1986, vol. 49, no. 23, 1572-1574

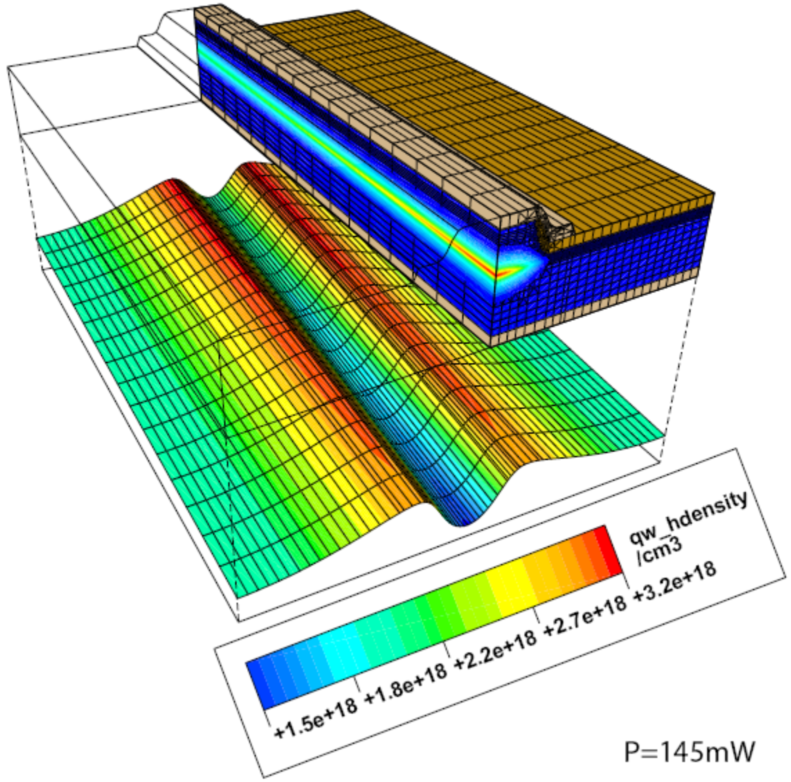
S. Yamamura, K. Kawasaki, K. Shigihara, Y. Ota, T. Yagi and Y. Mitsui, "Highly Reliable Ridge Waveguide 980nm Pump Lasers Suitable for Submarine and Metro Application," OFC 2003, vol. 1, 398-399

J.H. Marsh, C.J. Hamilton, "Semiconductor laser," U.S. Patent No. 6760355

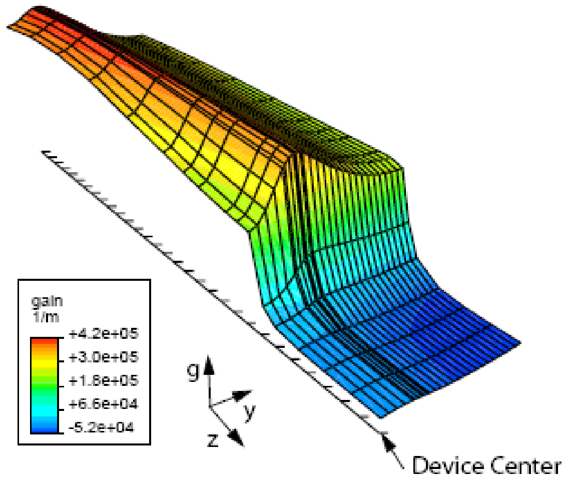
intense

Effect of front section isolation (*)

Standard Contact



Truncated Contact

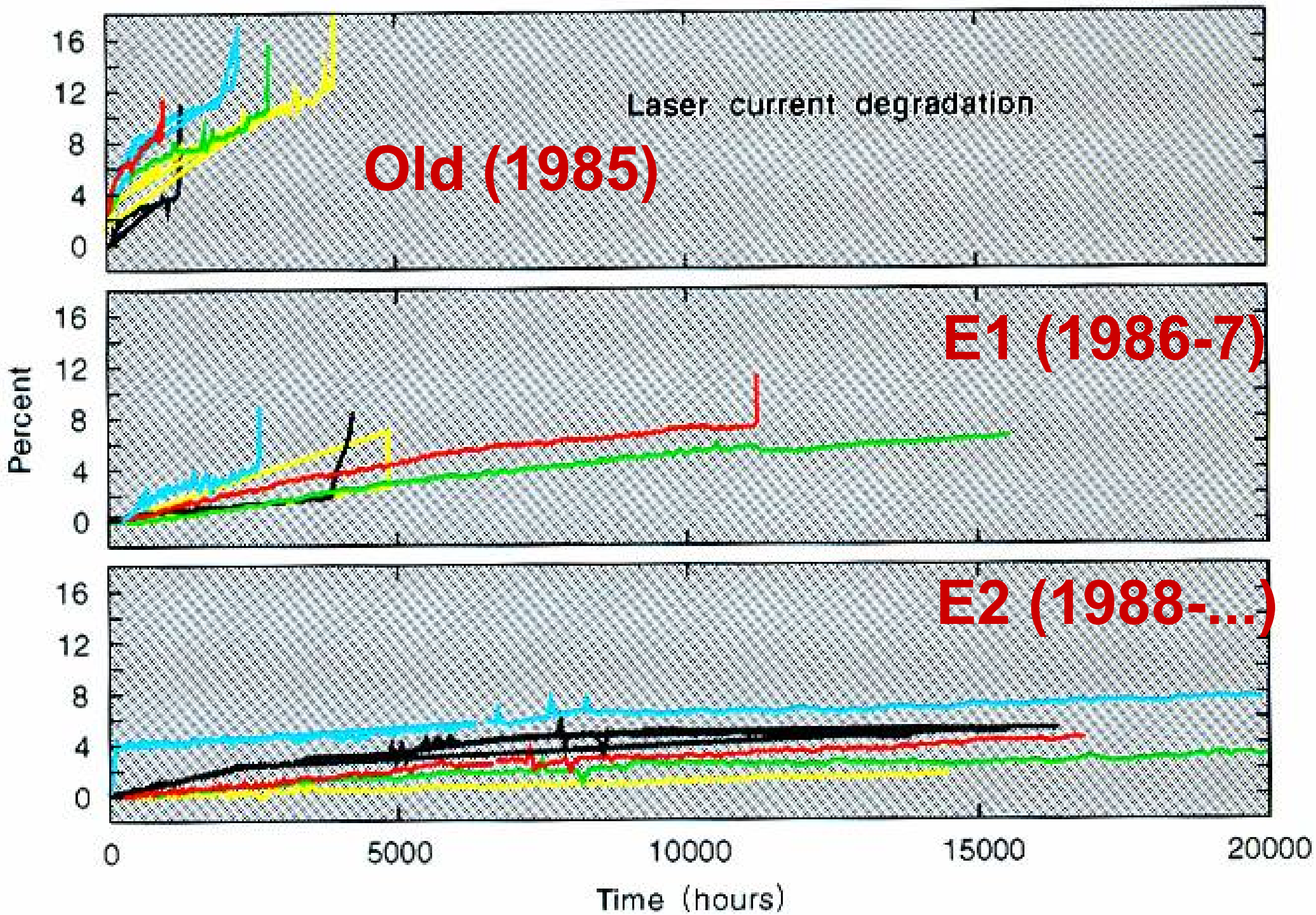


Reduction of current injection into front section (reduced local heating)

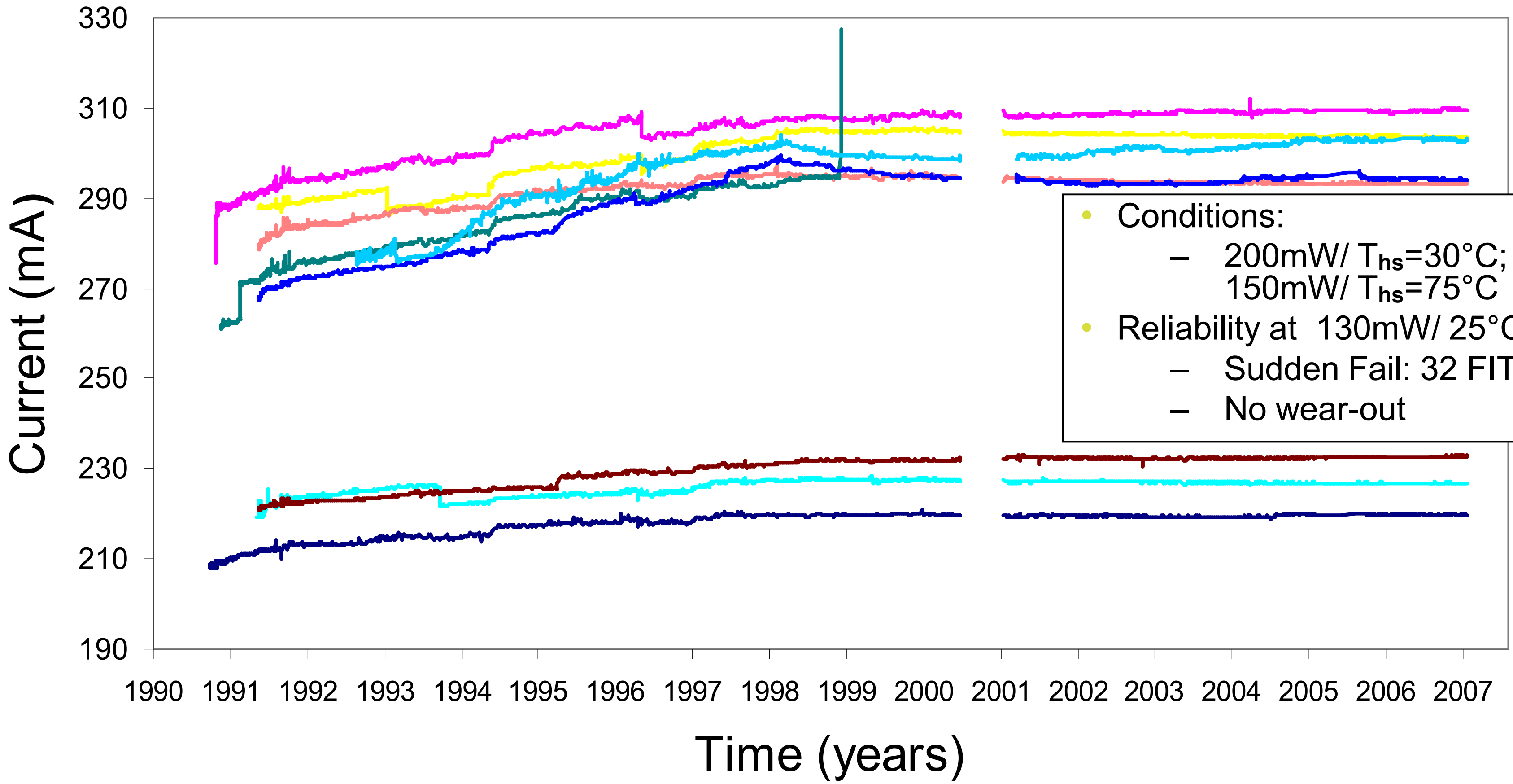
Reduction of free carriers (impact on the gain profile)

***Source: Prof. B. Witzigmann, ETH-Zurich**

Single Mode Pump Diode:
Facet passivation at 830nm and 980nm

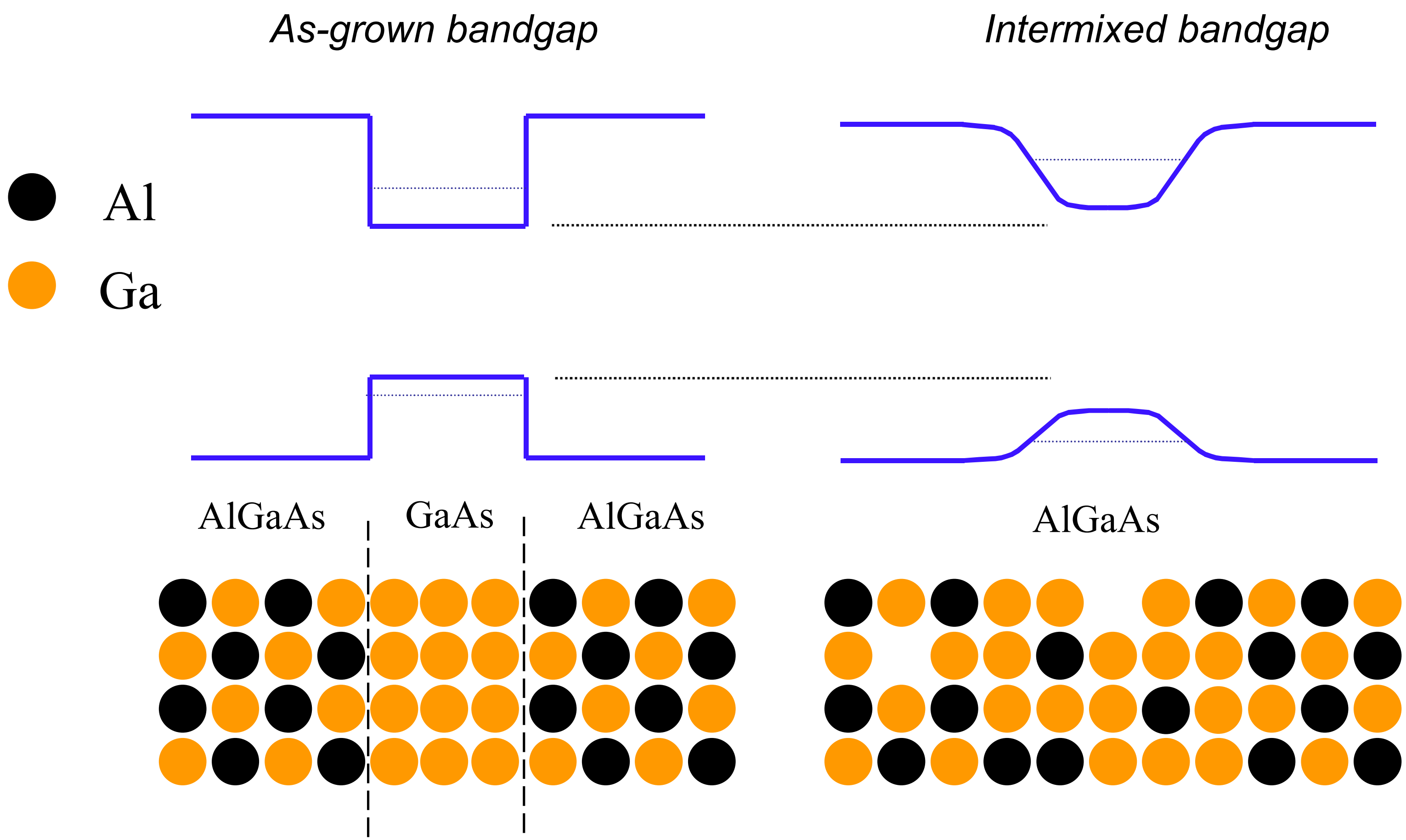


980nm Methuselah Lasers: 17 Years of Stress Test



- Conditions:
  - 200mW/ T_{hs}=30°C; 150mW/ T_{hs}=75°C
- Reliability at 130mW/ 25°C:
  - Sudden Fail: 32 FIT
  - No wear-out

QWI process concept



QWI allows bandgap tuning in selected areas of the chip

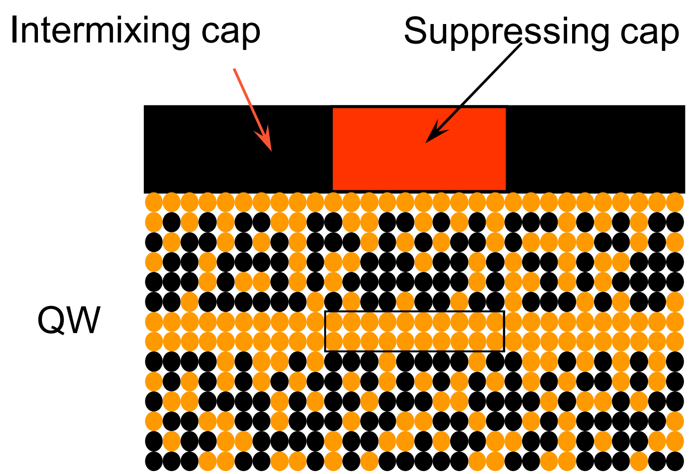
QWI Process Steps

Intense QWI technology enables high power/brightness lasers to be produced in a manufacturing environment

- Dielectric caps are deposited on surface of wafer
- Wafer is annealed
- Quantum wells intermix with adjacent material altering the bandgap wavelength
- Wavelength change depends on properties of dielectric cap

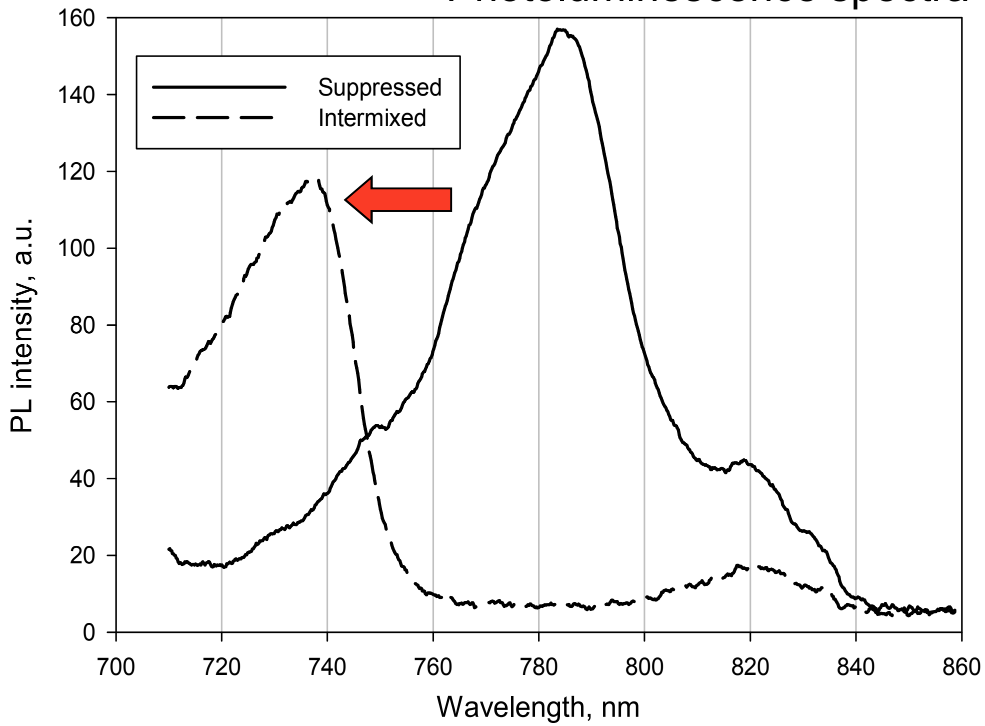
QWI works in a variety of materials and wavelengths

- 808 nm SQW material used in this work



High Temperature Anneal

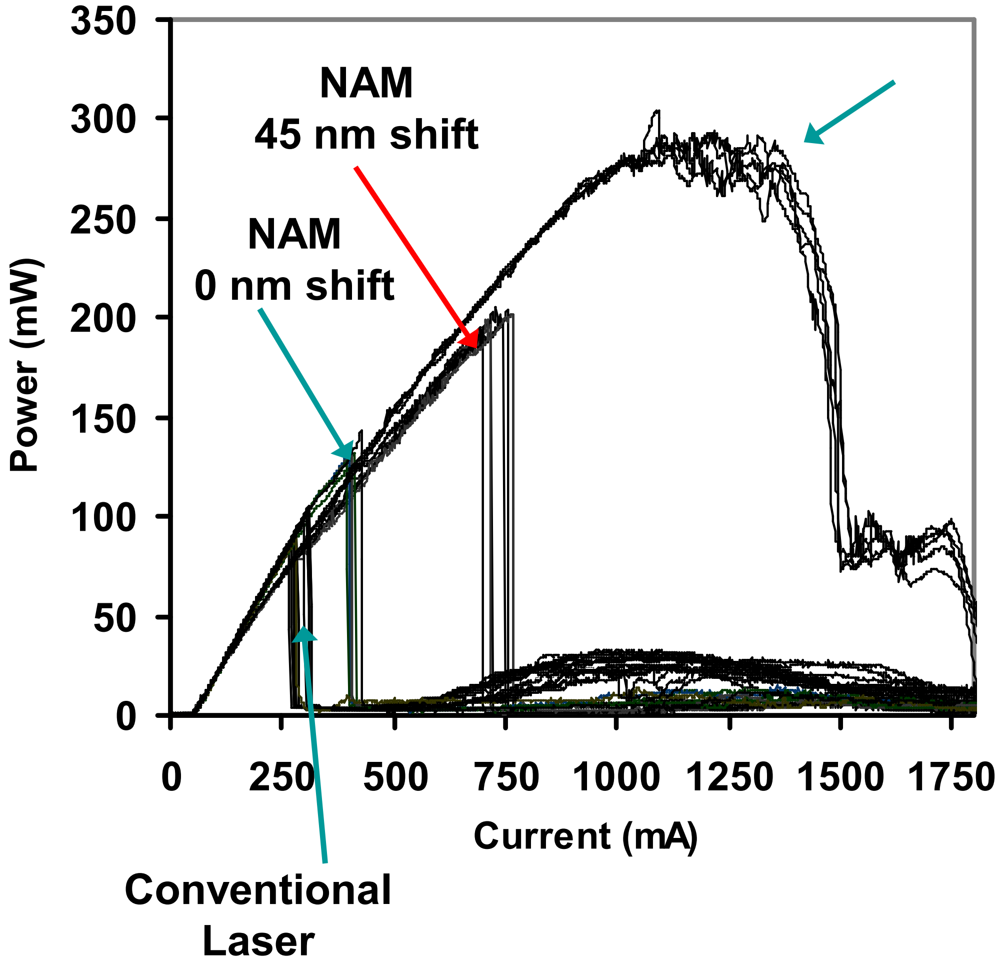
Photoluminescence spectra



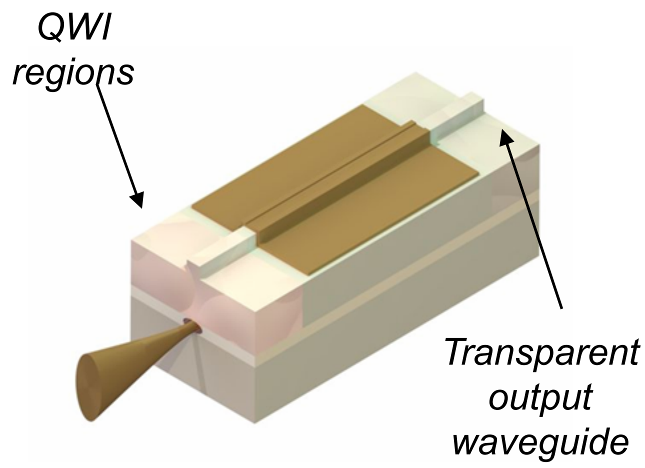
intense

Avoiding COMD: QWI (quantum well intermixing)

- *Uncoated* 830 nm lasers
- Test conditions: Initial CW measurement followed by a pulsed *L-I*



NAM
65 nm shift

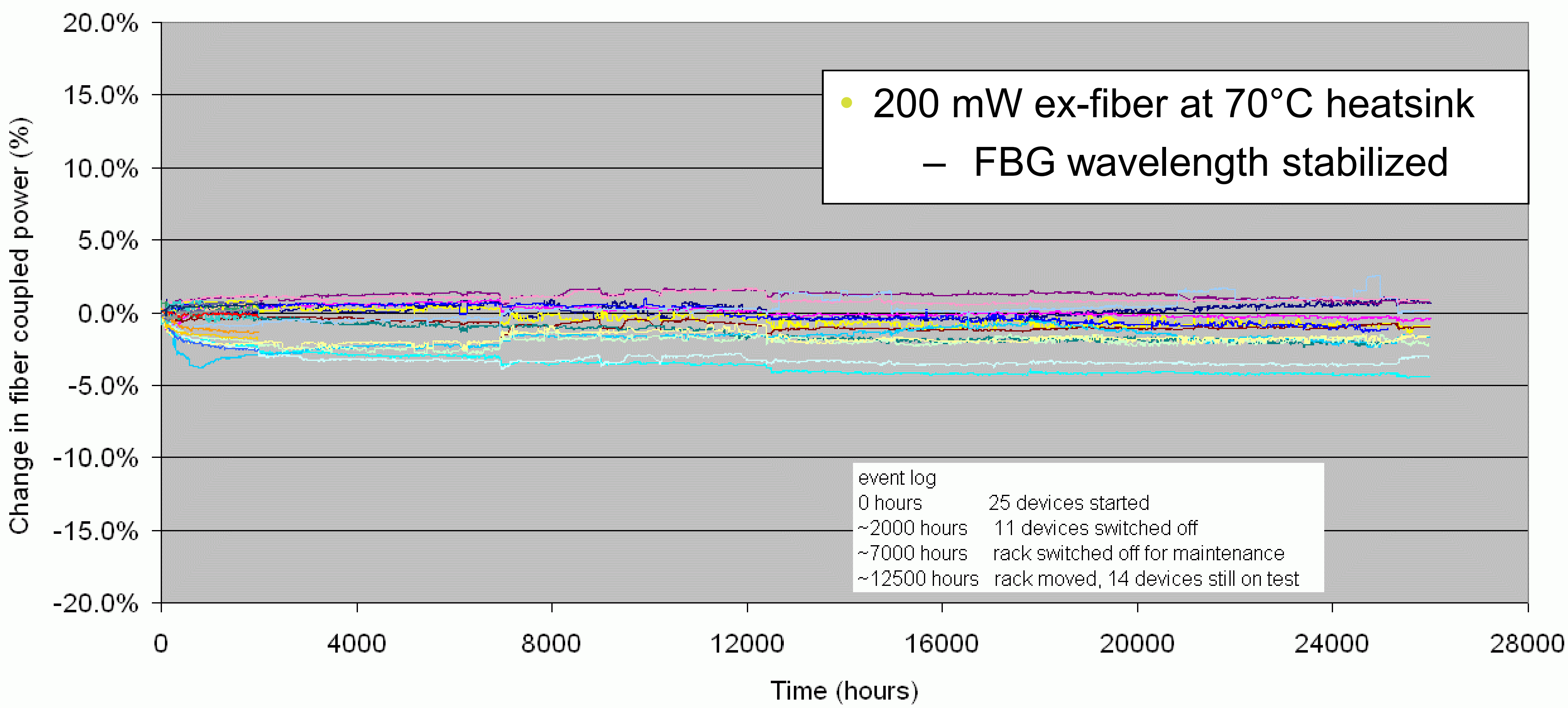


Increase of the bandgap close to the facet region

Reduction of free carriers

Reduction of local absorption

3 Years 980 nm MiniDIL Operation

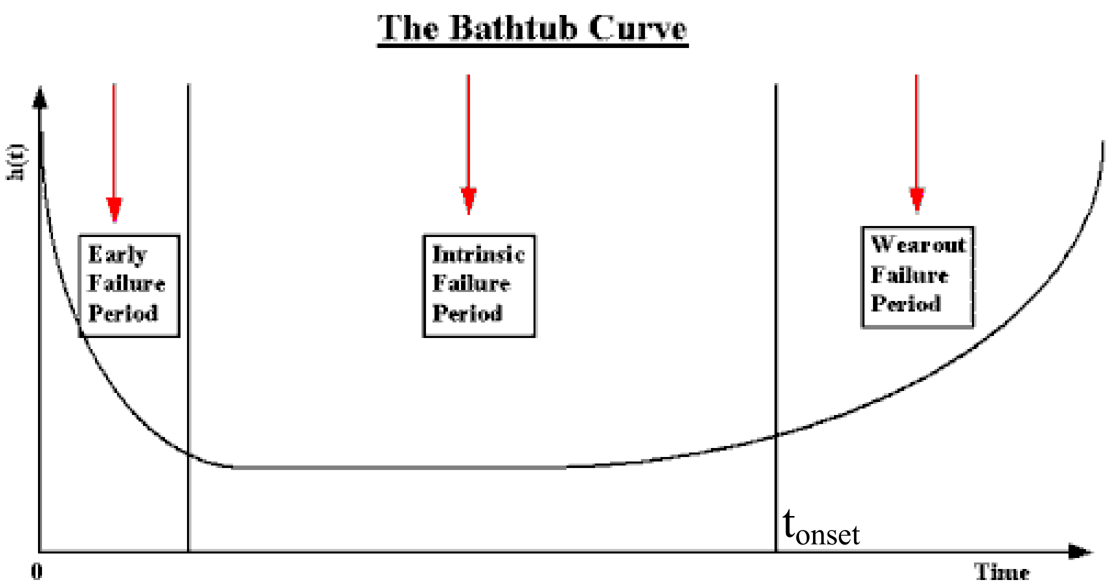


Classical life test strategy: single emitter devices

Assumptions

- Known failure modes
- Laser diode lifetime follows "bath tube" curve
- Infant mortality rate is vanishing or can be screened out by burn-in
- Constant failure rate (intrinsic period) is determined by sudden death (or a short wear out period followed by sudden death)
- Wear out is expected to kick in after guaranteed device life time

- Constant failure rate can be described by: $FR \propto I^x P^y \exp(-E_a / k_b T)$



Lifetest: results stress cell matrix

- All CoS post burn-in (300h, 1260mA, 85C)

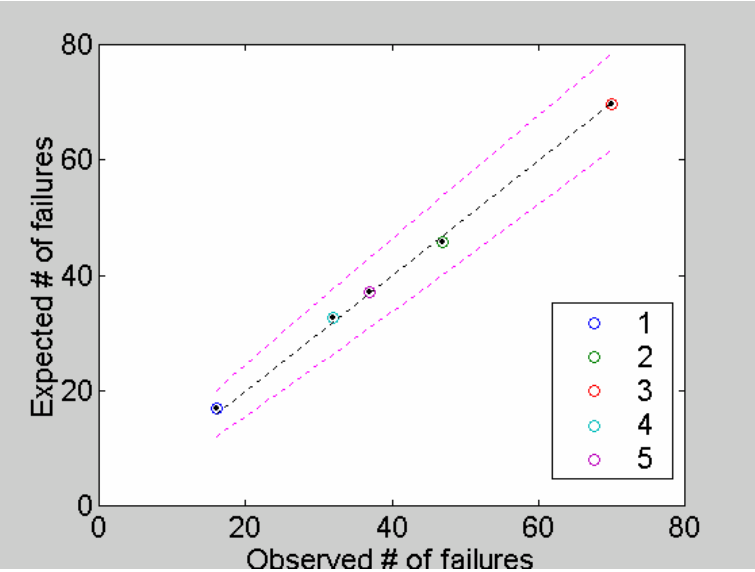
Cell	Power	Current	Junction (Case) Temperature	Starts	Device Hours	Failures
1	820 mW	1030 mA	89°C (60°C)	196	892'362 h	16
2	820 mW	1130 mA	116°C (80°C)	193	772'622 h	47
3	820 mW	1260 mA	140°C (95°C)	141	460'990 h	70
4	820 mW	1340 mA	151°C (100°C)	91	142'324 h	32
5	680 mW	1080 mA	147°C (110°C)	93	369'253 h	37
				714	2'637'551 h	202

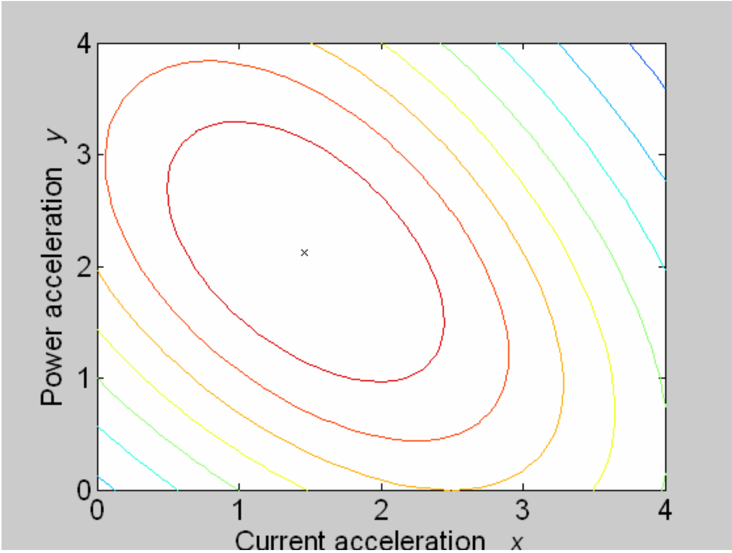
- 16 lots lots started
  - 2 excluded (atypical)
  - LV not yet applied
  - No selection after burn-in

$$Fails = FR \cdot \left(\frac{j}{j_0}\right)^x \cdot \left(\frac{p}{p_0}\right)^y \cdot e^{\frac{-E_a}{(kT-kT_0)}}$$

- Assume functional dependence Derive
- Derive parameters for which cell test results are most likely
  - Maximum likelyhood analysis

Maximum Likelyhood analysis: Ea:=0.45eV; x,y free





- X and y are anticorrelated, x+y=3.6
- FR base failure rate: At 930 mA, 36°C junction temperature (25°C case)

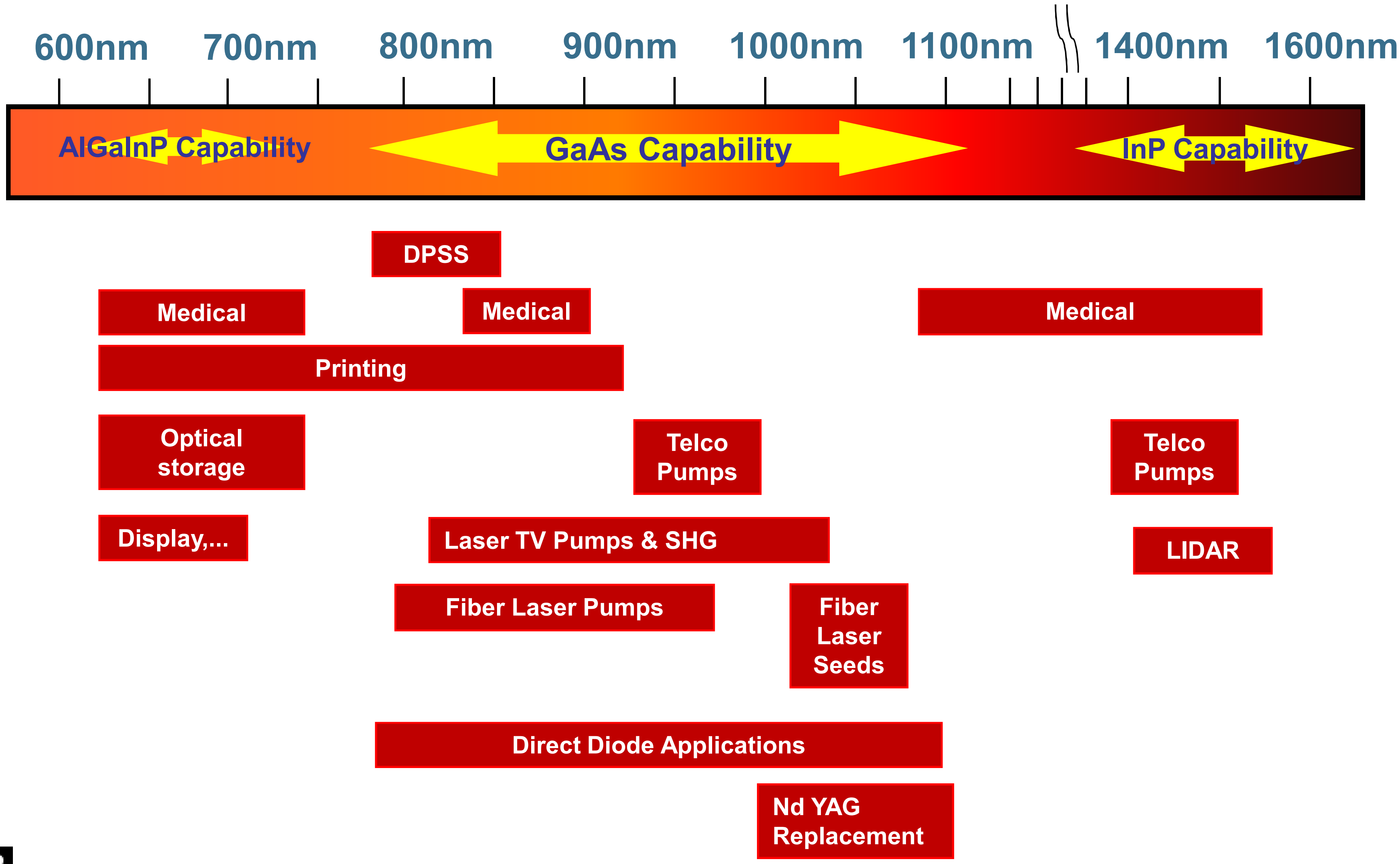
x free, y free; Ea := 0.45 eV

x	1.5	
y	2.1	
E_a	0.45	eV
FR	1'376	FIT
P	99%	

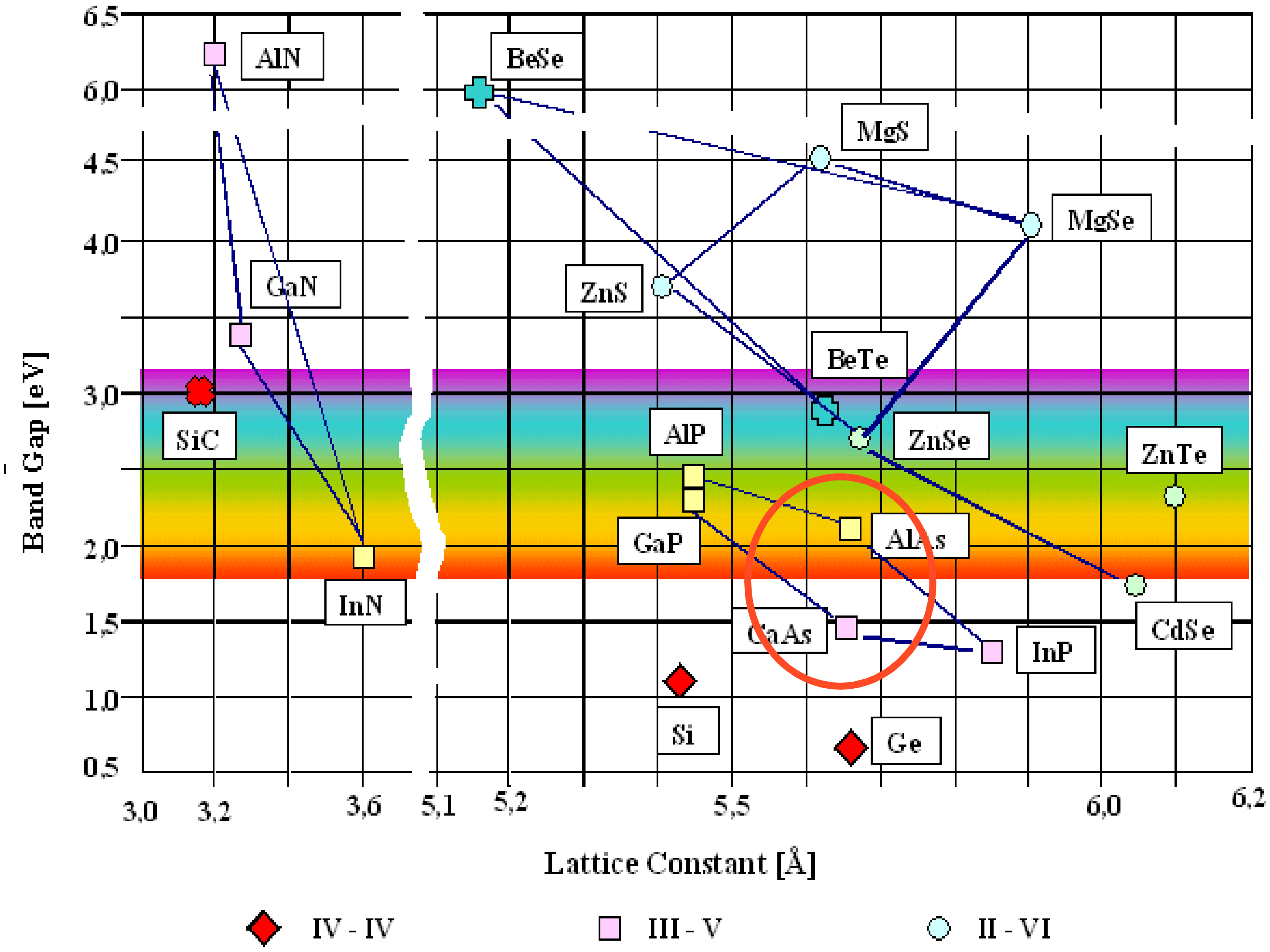
$$Fails = FR \cdot \left(\frac{j}{j_0}\right)^x \cdot \left(\frac{p}{p_0}\right)^y \cdot e^{\frac{-E_a}{(kT - kT_0)}}$$

intense

Wavelength Range for major industrial applications / technologies requiring (red / MIR) HPL



Materials for Semiconductor Laser Processing



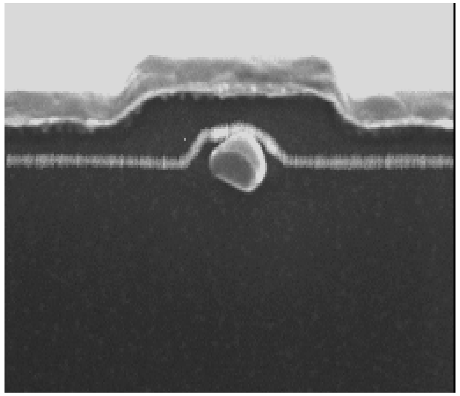
Broad Area

Broad Area

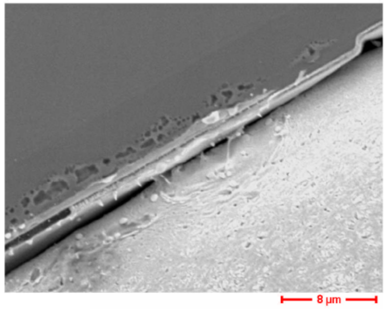
High powers are limited by power density at facet

-> Use a wider facet, broad area laser diode:

1. higher heatload: Need to solder devices junction down to heatsink
   – Cooling
2. This leads to degradation of beam quality, i.e. multi lateral mode behavior
   – Coupling to fiber



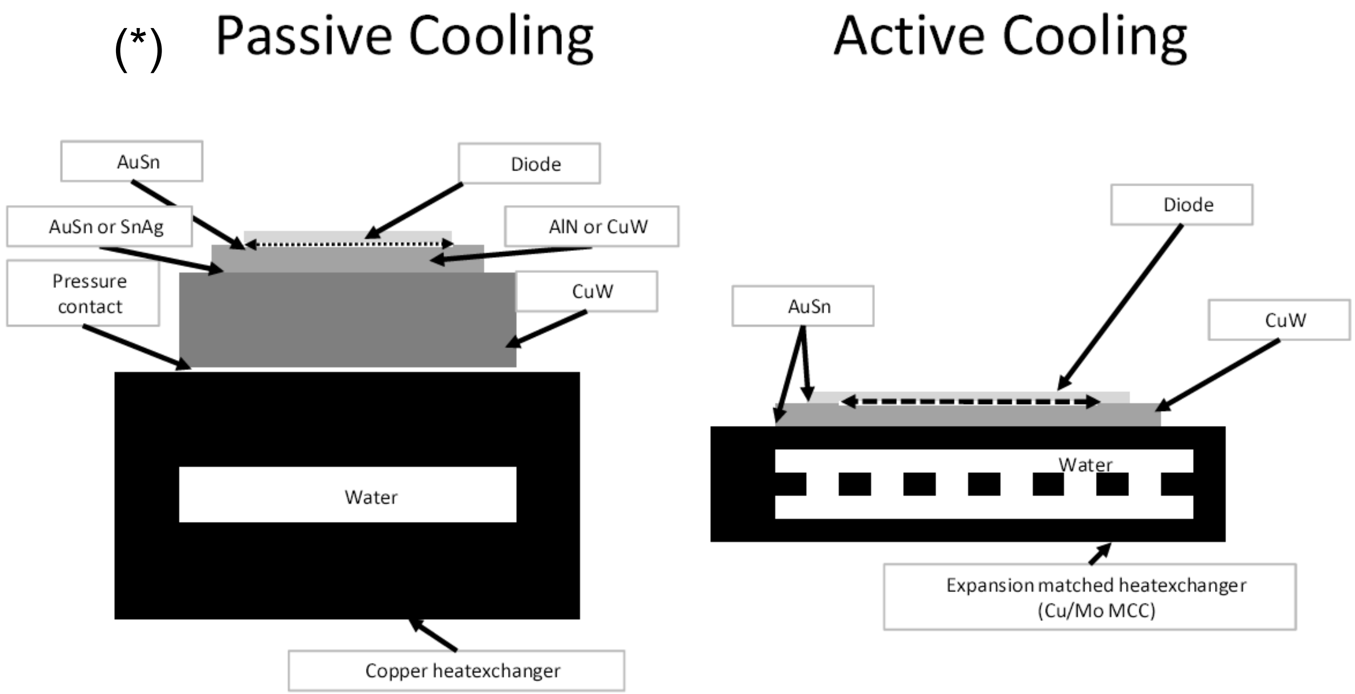
Narrow Stripe: J-up



Broad Area: J-down

Cooling

Types of coolers for hard solder bar mounting



- Passive Cooling (copper heat sink with heat exchanger -> Water or Air cooled)
- Active Cooling of high power bars (micro, meso or macro channel cooler)

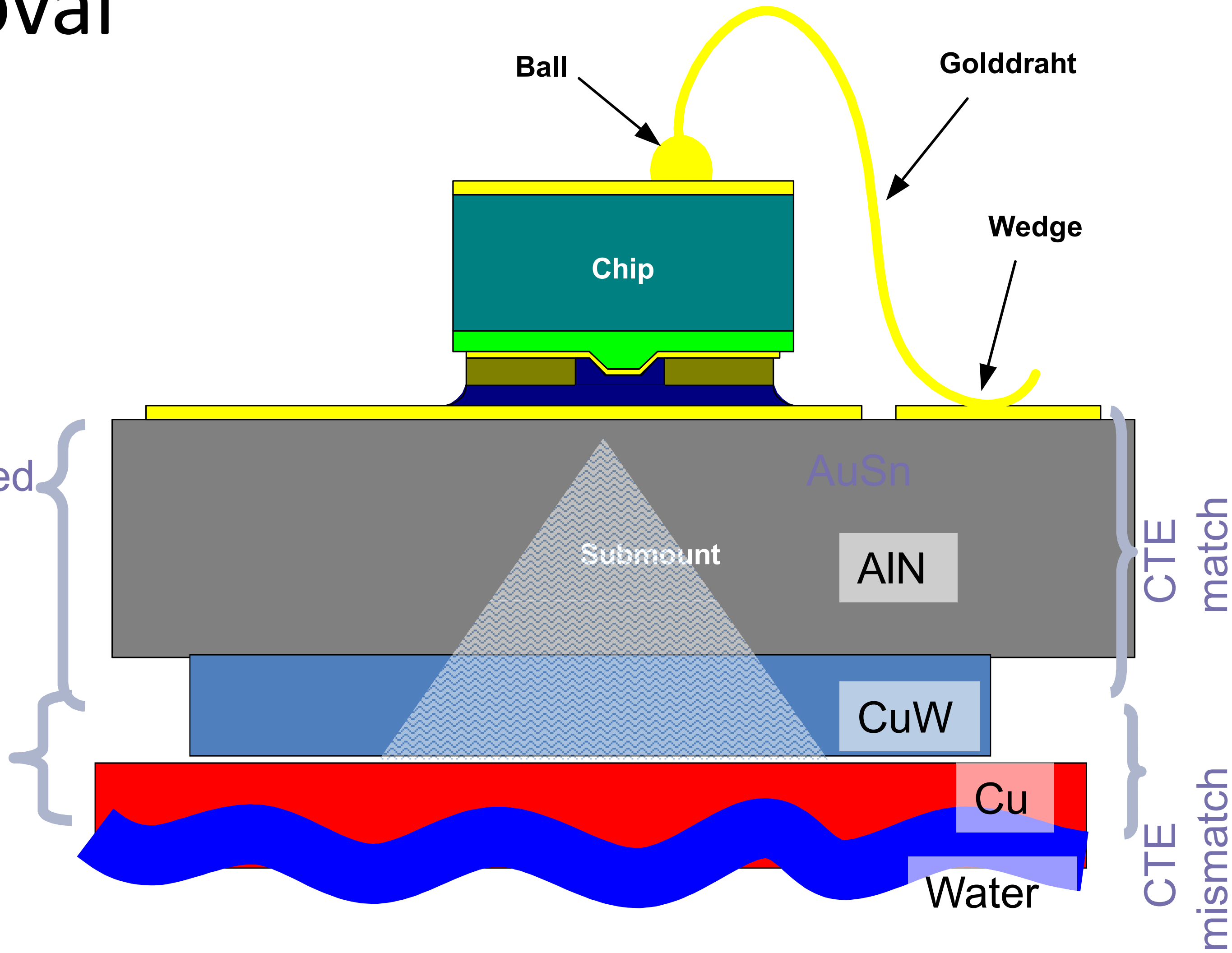
- Active cooling of single emitter devices (TEC and heat exchanger)

* Christoph Harder; “Chapter: Pump Diode Lasers”, Optical Fiber Telecommunications V A (Fifth Edition), Components and Subsystems, Editor: *Ivan P. Kaminow, Tingye Li and Alan E. Willner, pp. 107-144.*

9xxnm Multimode Pump Diodes
Heat removal

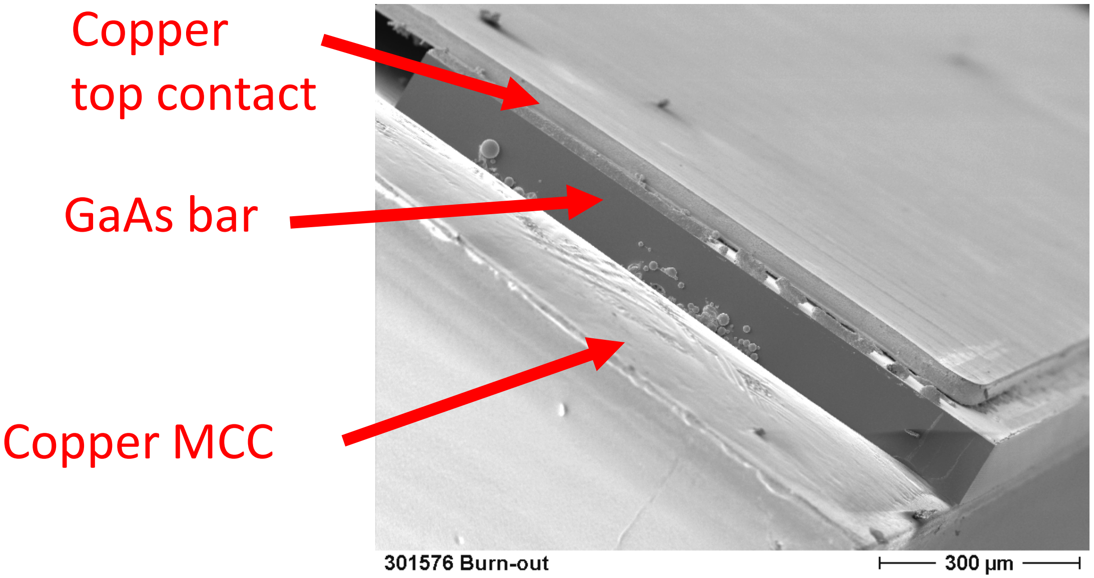
Soldered to expansion matched materials for heat spreading

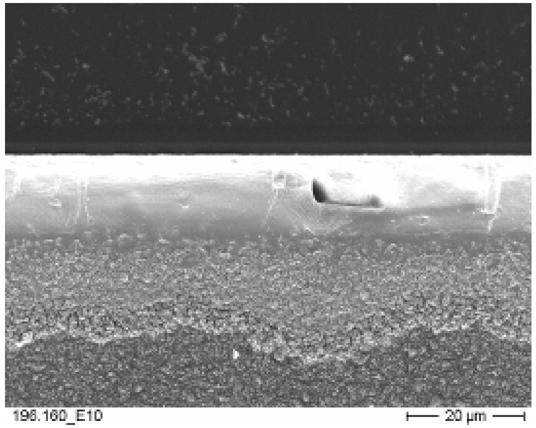
Mechanical pressure thermal contact to copper heatsink

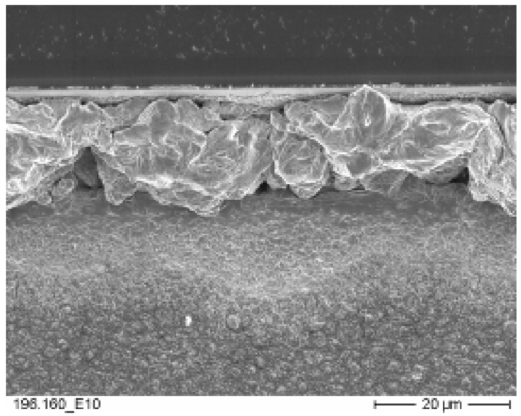


Cooling: Micro Channel Coolers

Bar Blow up (Indium solder issue)

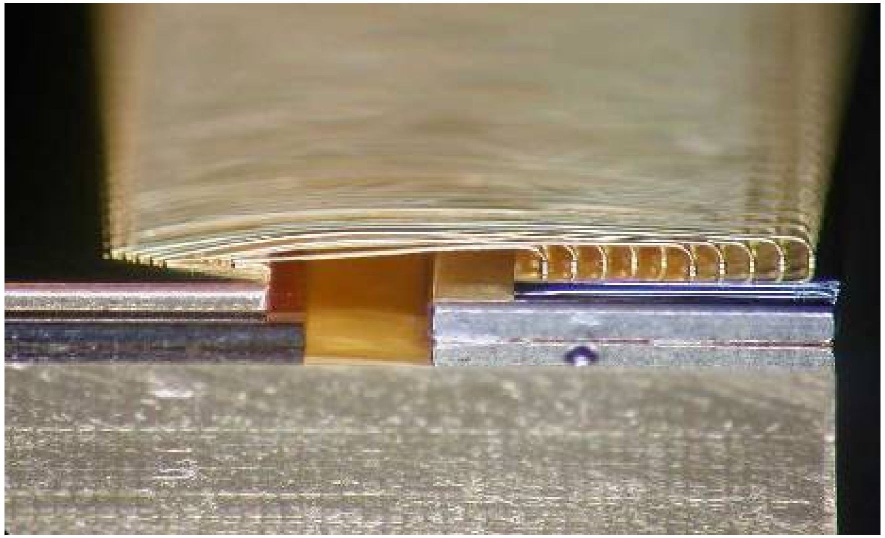


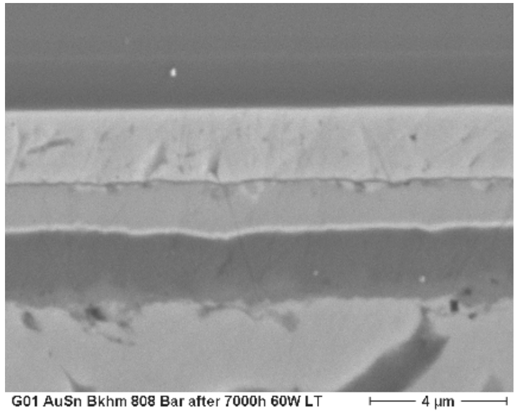




- Indium is used to overcome cte differences between GaAs and copper
- Indium is stable under CW operation but not under on/off operation
  - Increased thermal resistance leads to bar blow up

AuSn technology on MCC

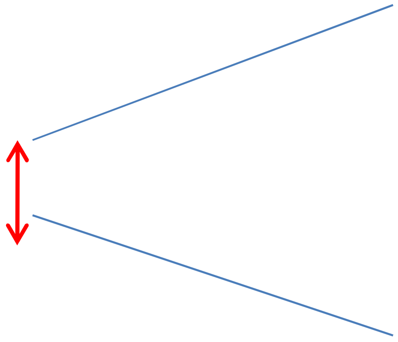




AuSn solder unchanged after 7000 h LT
(40 Mega cycles of hard on/off)

- Hard solder (AuSn) attach to expansion matched heatspreader of bar
- Low smile assembly of bar on submount to MCC (this interface is still cte mismatched)
- Low stress cathode contact with wire bonds

Beamquality



Beam with aperture radius of “a” and divergence of “NA”
The beam parameter product and the etendue is

- BPP=a*NA
- Etendue=$(\alpha * NA * \pi)^2$, or a*b*NA_x*Na_y*π^2 for an elliptical beam

•

The minimum beam parameter product and etendue (corresponding to a single lateral mode) is given by

- BPP=a*NA=Lambda/ p =0.32um*rad for lambda=1um
- Etendue=(a*NA* π)^2=Lambda^2=1*10^{-8} cm^2 ster for lambda =1um

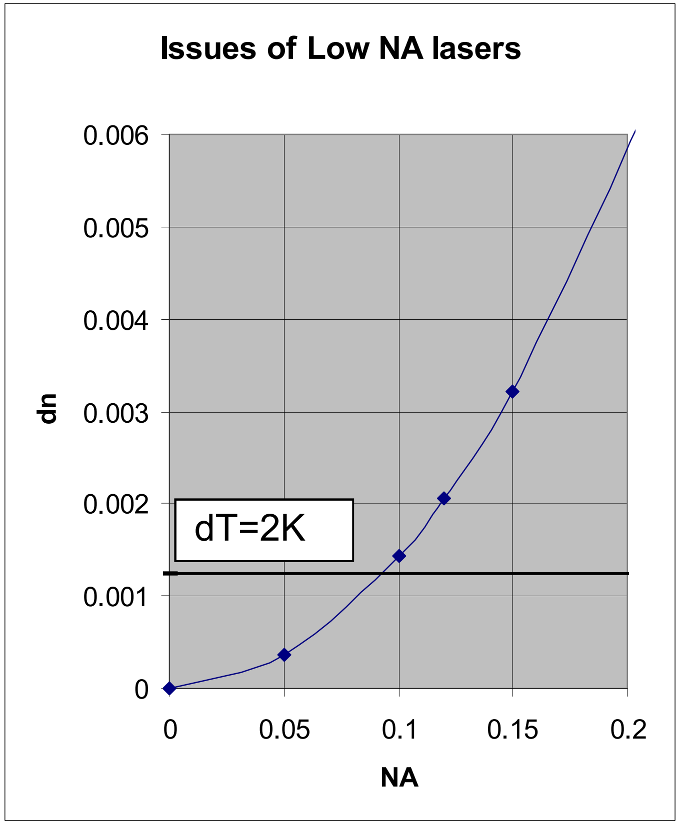
9xxnm Multimode Pump Diodes: Thermal Blooming at high Power

$NA = n \sin \theta_{max} = (n_1^2 - n_2^2)^{1/2} = (2*n*dn)^{1/2}$

$dn = dn/dT * dT$ $\qquad dn/dT = 3*10^{-4}$

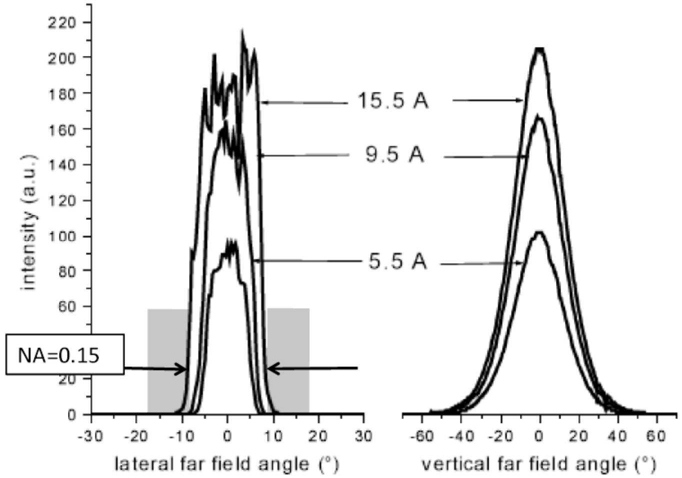
- Low NA laser
  - Achieved by low dn waveguide
- dn
  - Lateral temperature profile
  - dT=5K -> NA=0.09

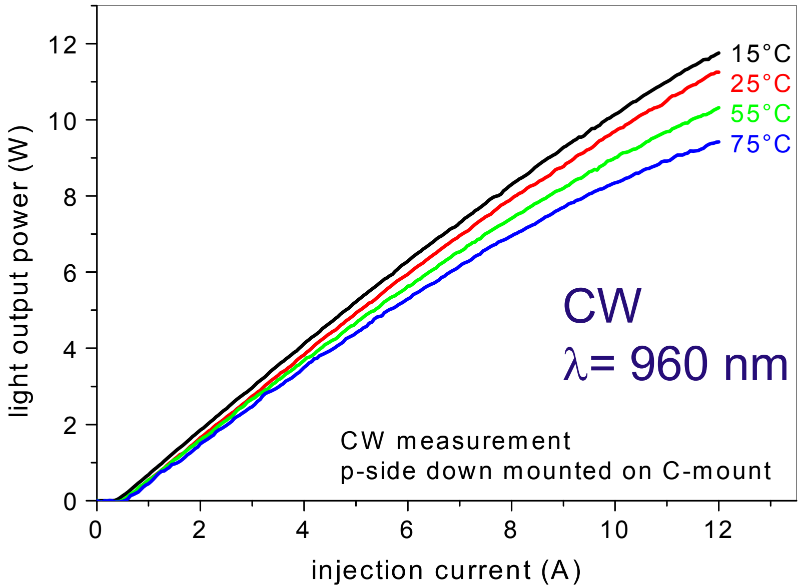
- Keep dT<2K

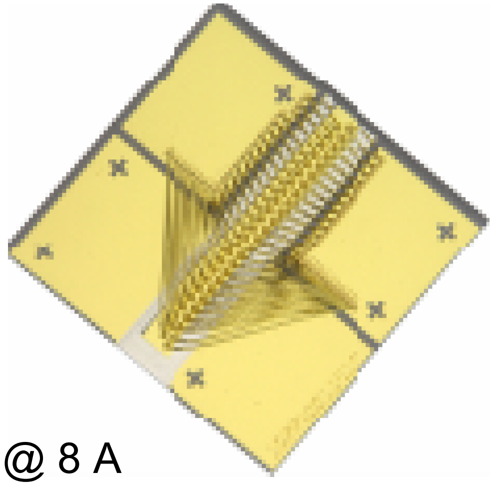


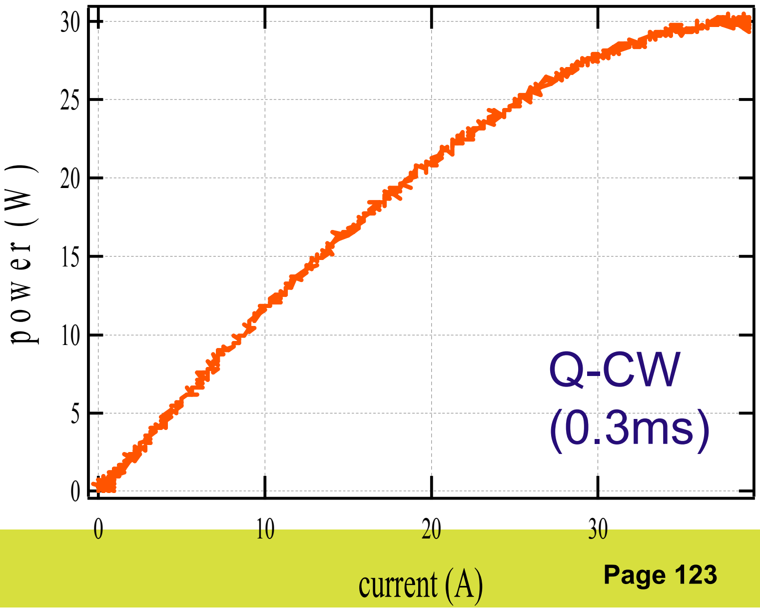
$dn = 1/2*(NA/n)^2$

SES8-9xx-01 performance



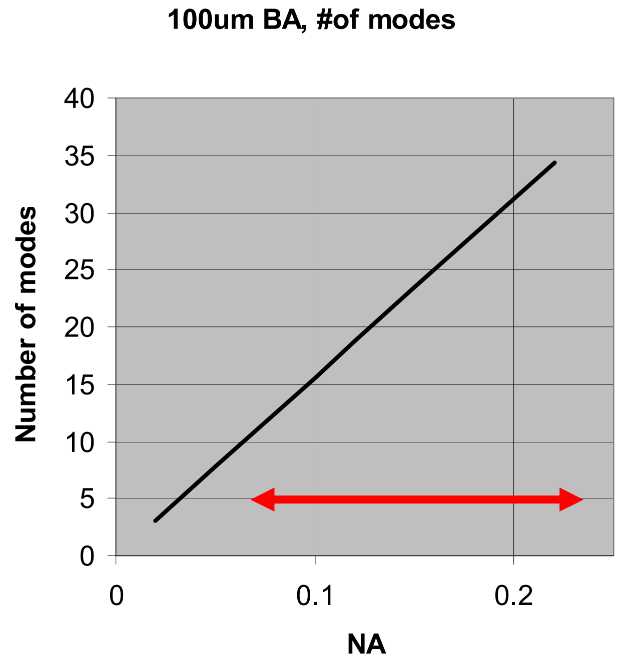






- Electro-Optical
  - Power: 8 W @ 8 A
  - Reliability: <5% fail in 10‘000h

Number of Lateral Modes in BA chip



- Low NA broad area laser radiance:
  - Closing in on single mode lasers
  - 8W from NA=0.15NA: 400mW per lateral mode
- Reduce NA of broad area laser to increase radiance
  - NA dominated by thermal blooming
  - ->Need chip with very high power conversion

High Power Laser Diodes: 20 years ago

- Narrow stripe laser:
  - COMD: Mirror blows up at high powers

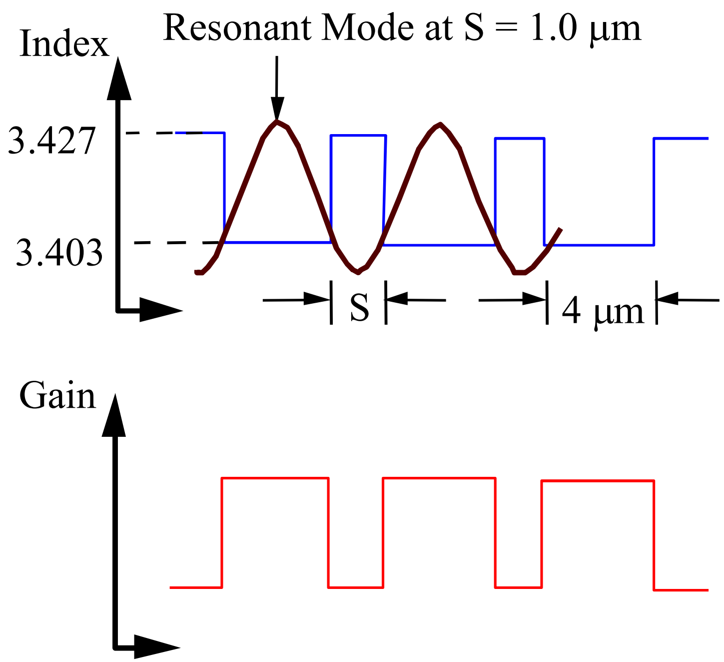
-> Spread beam to decrease power density at facet:

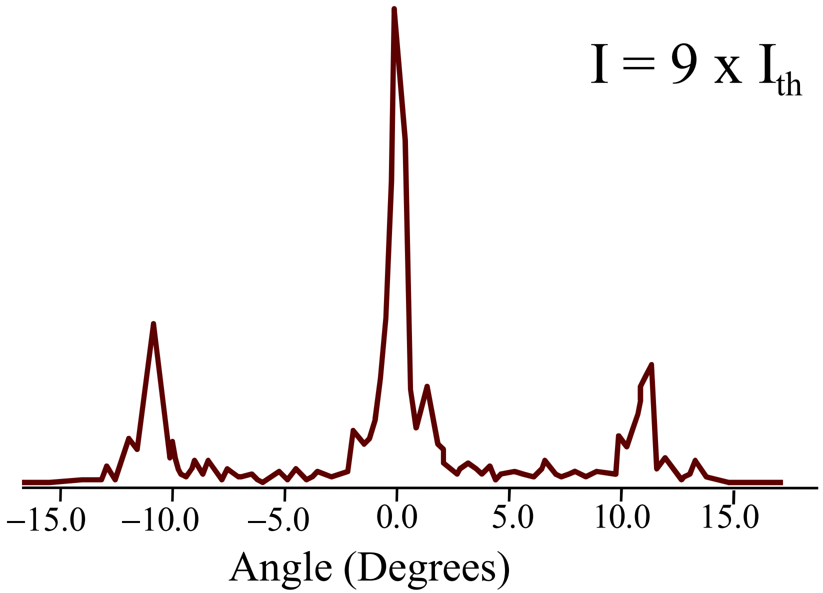
Coherent arrays
Surface grating lasers
MOPA
Taper Laser
Alpha DFB
VCSEL

In the 80‘

Never achieved reliable beamstability for high volume applications

1-D Active Photonic Crystal ⇒ROW Array





Resonant (lateral) leaky-wave coupling

⇓

Bragg condition exactly satisfied

⇓

(20 - 40)-element phase-locked arrays

$\theta_{1/2}$= 0.67° = 1.8 x D.L.

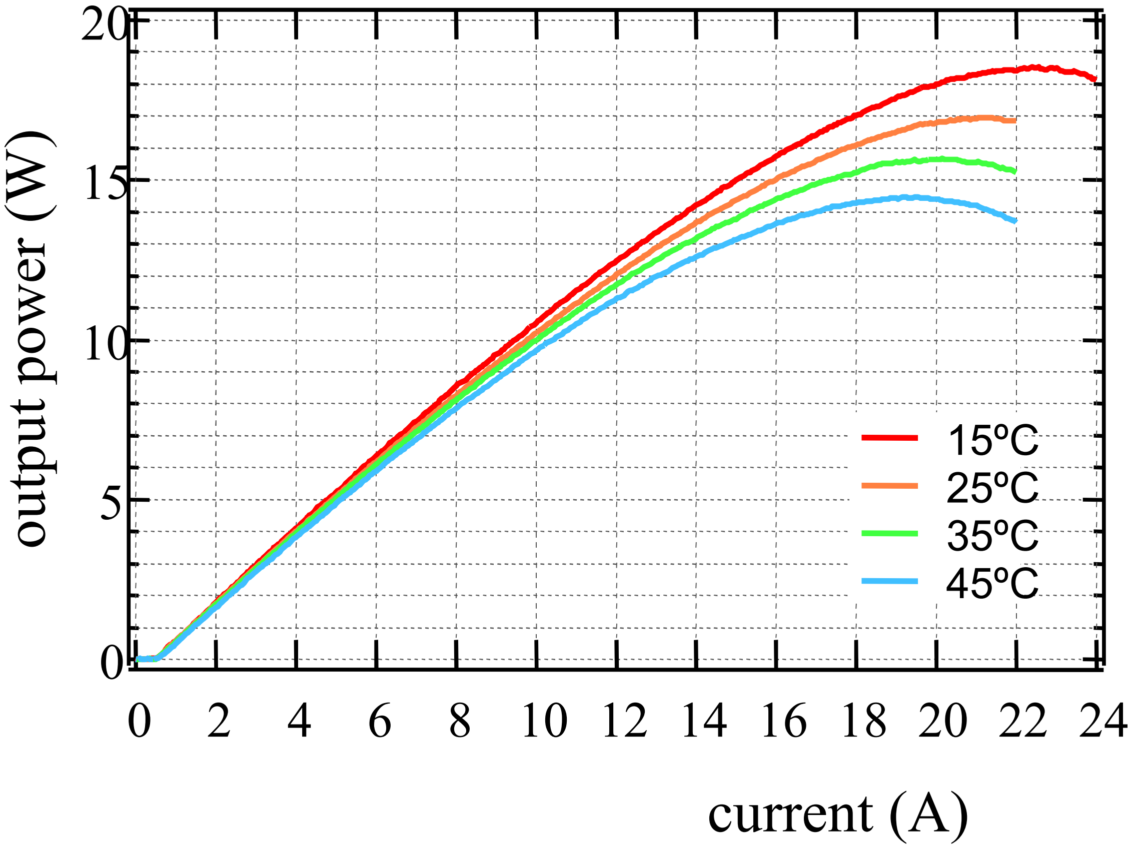
η_p= 23%

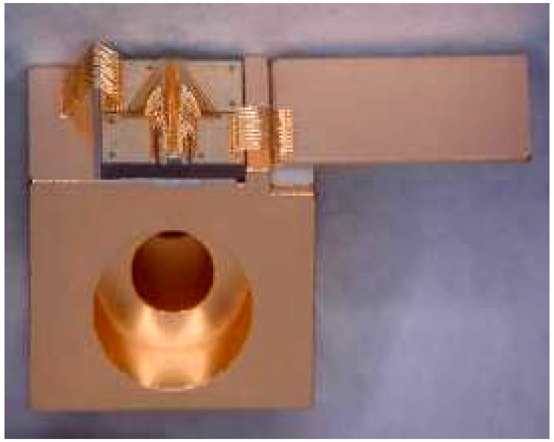
1.0 W power in main lobe

40-element ⇒ 200 μm aperture *

* H, Yang et al., Appl. Phys. Lett., **76**, 1219 (2000)

9xxnm MM Pump Diode: CW on C-mount





- ~90 um emission width
- 19 W CW roll over power at 15 C
- Temperature insensitive: T_o ~ 200K

- **At 35 C**
  - **9 W at 9 A**
  - **>65% conversion efficiency at 9W**

Etendue Matching

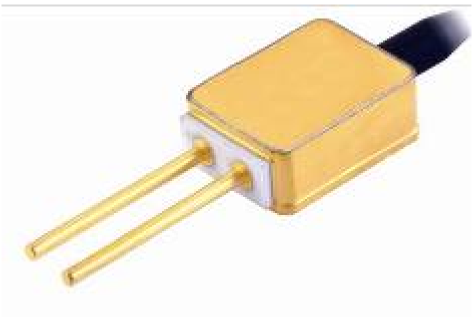
Diode Laser	Beam Width [um]	NA [rad]	Fast axis BPP [um rad]	Slow axis BPP [um rad]	Etendue [um^2 sr]
Single mode diode	5	0.12	0.3	0.3	1
Standard BA diode at low power	100	0.05	0.3	3	8
Standard BA diode	100	0.09	0.3	5	14
Low NA wide BA diode	200	0.09	0.3	9	28
Low NA minibar	3'200	0.07	0.3	112	340
Fiber	Core Diameter [um]	NA [rad]		BPP [um rad]	Etendue [um^2 sr]
SM fiber	5	0.12		0.3	1
Input fiber for fiber combiners	105	0.15		8	610
Standard material processing delivery	200	0.22		22	4'800
High power material processing delivery	400	0.22		44	19'000
Fiber of cladding pumped laser	400	0.46		92	84'000
High power material processing delivery	1'500	0.46		345	1'200'000

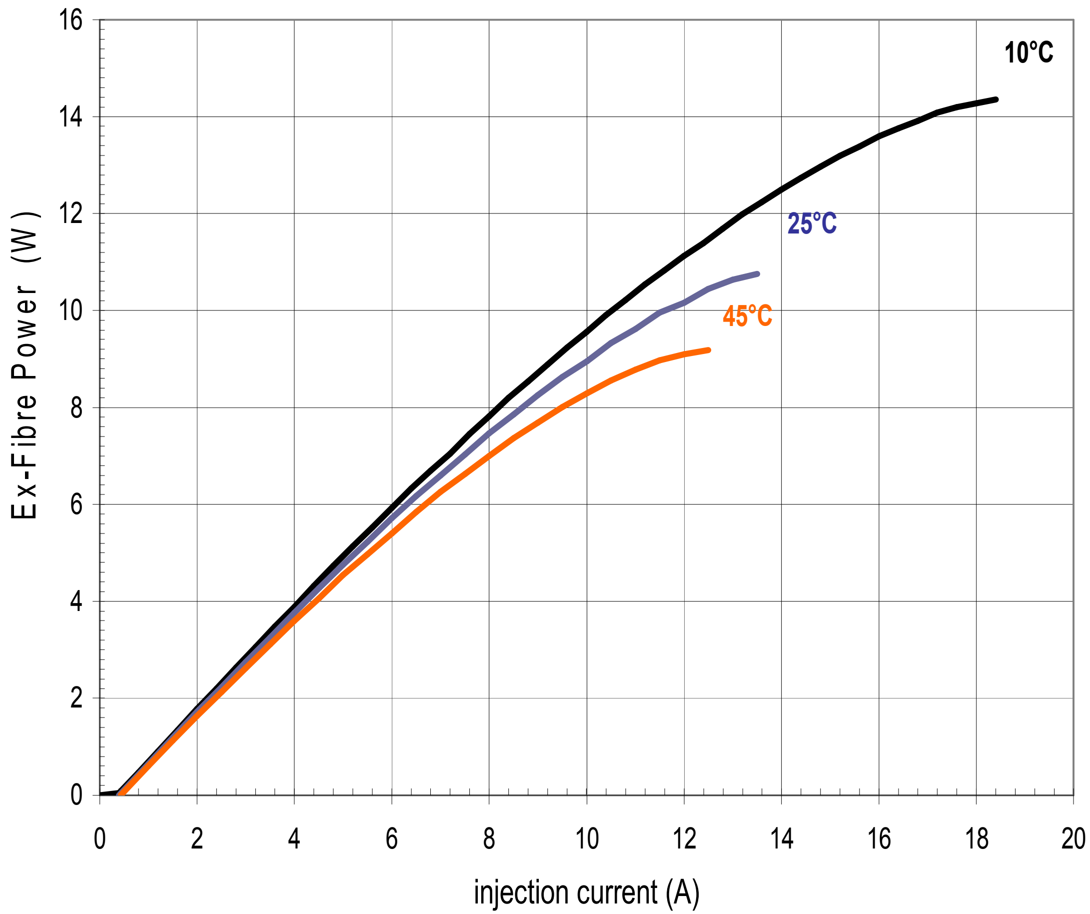
Theoretical limits:

- 4800 single mode lasers fit in a 200um/0.22NA fiber
- 350 Standard BA lasers fit in a 200um/0.22NA fiber

With polarization multiplexing and wavelength division multiplexing even mor diodes can fir in the fiber

MM Uncooled Module with >14W





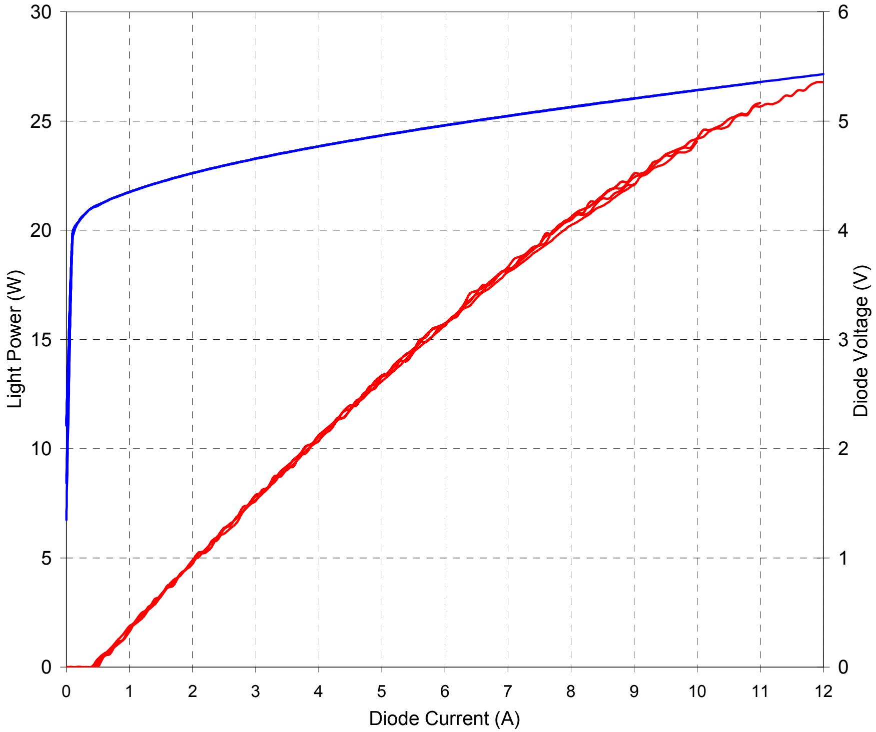
- Record Performance:
  - >14W @ 18A and 10 C T_{hs}
- Module fully qualified for industrial and telecom standards
  - 8W Industrial Product

Example II: 20W Multi-Emitter Module

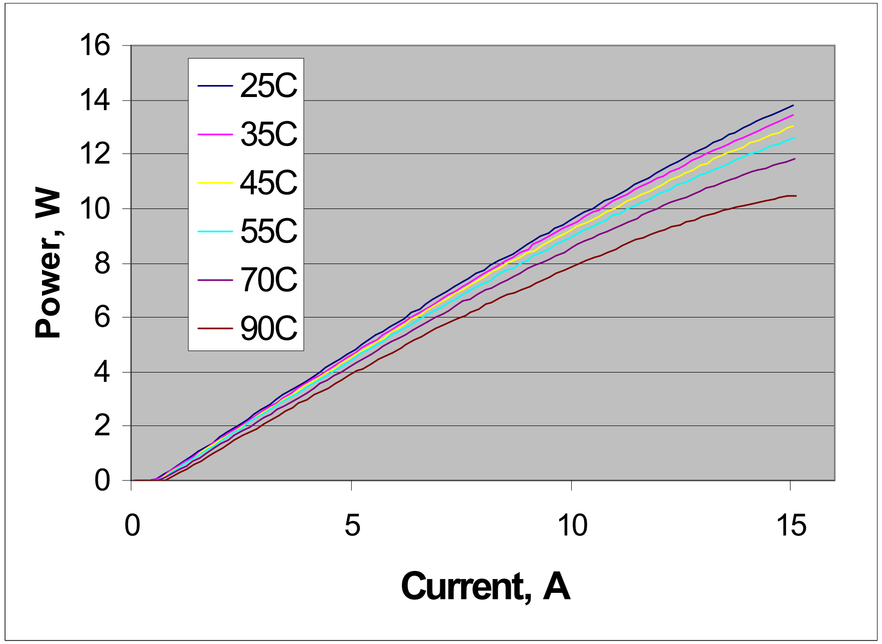
- **Module**
  - 3 single emitters inside
  - 2-pin package
  - 0.15NA or 0.22NA in 105um fiber
  - Floating anode/cathode
  - <u>1060nm blocking filter included</u>

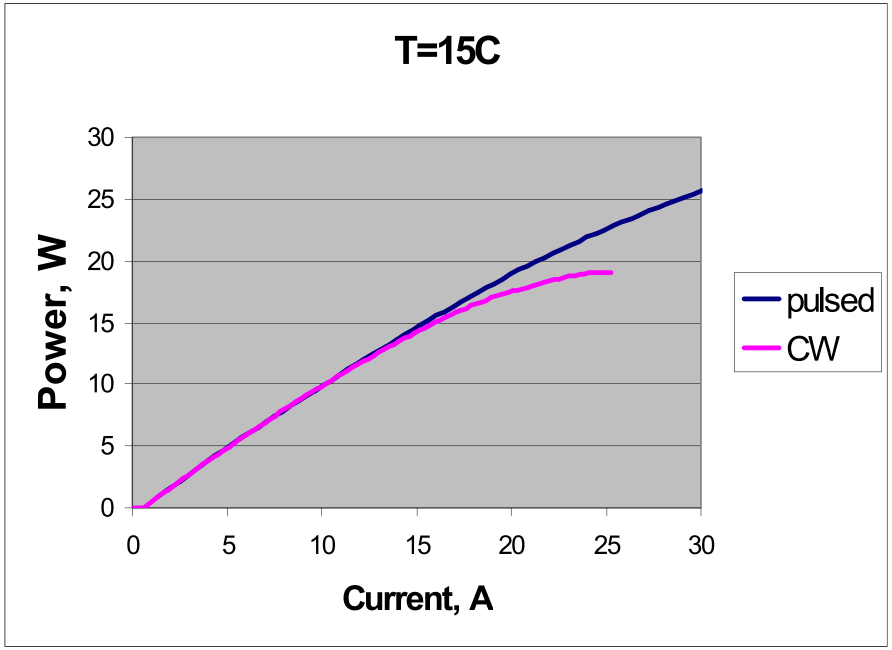
- **Electro-Optical**
  - Power: 20+W
  - Current: <<10A
  - Wavelengths: 915, 940, 960, 975nm

P-I -V Curves of 0.15NA 20W Modules at 25C:



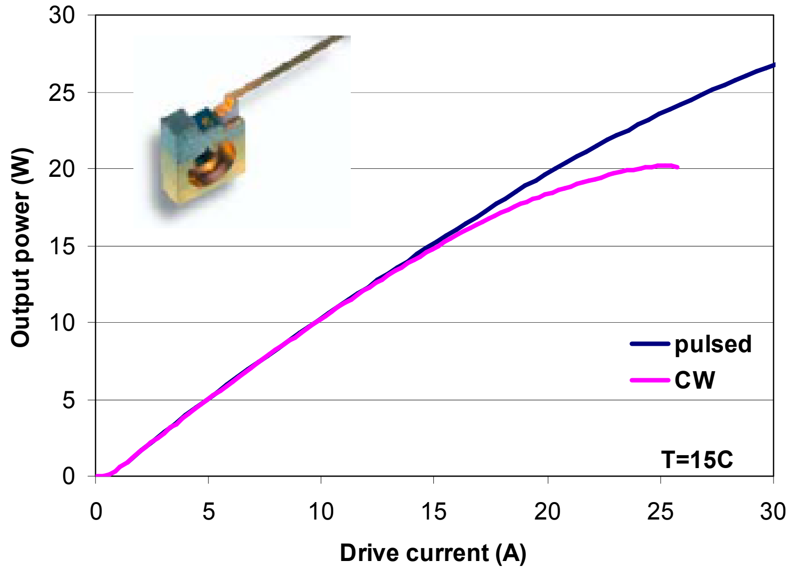
New generation 9xx broad area chip

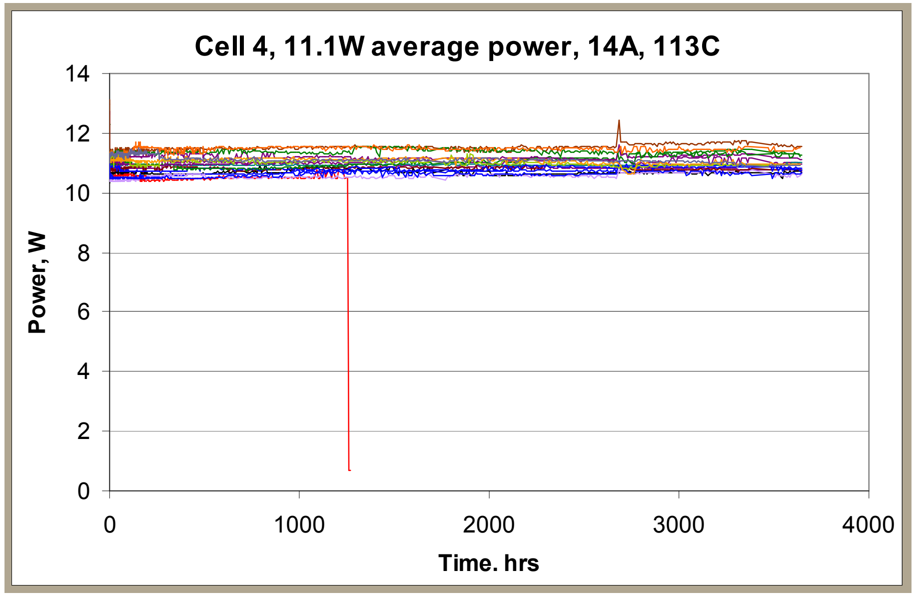


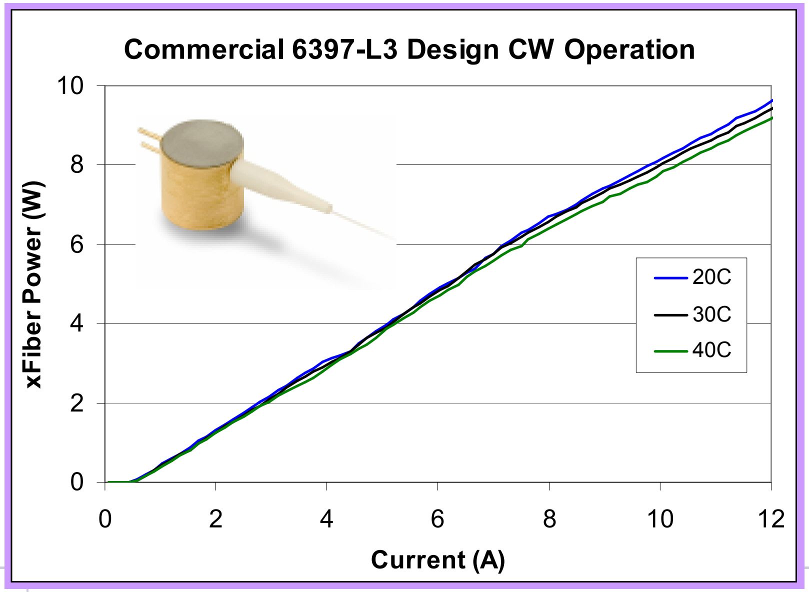


- 19.0W maximum CW power from ~ 100um aperture

JDSU 9XXnm Multi Mode Pump







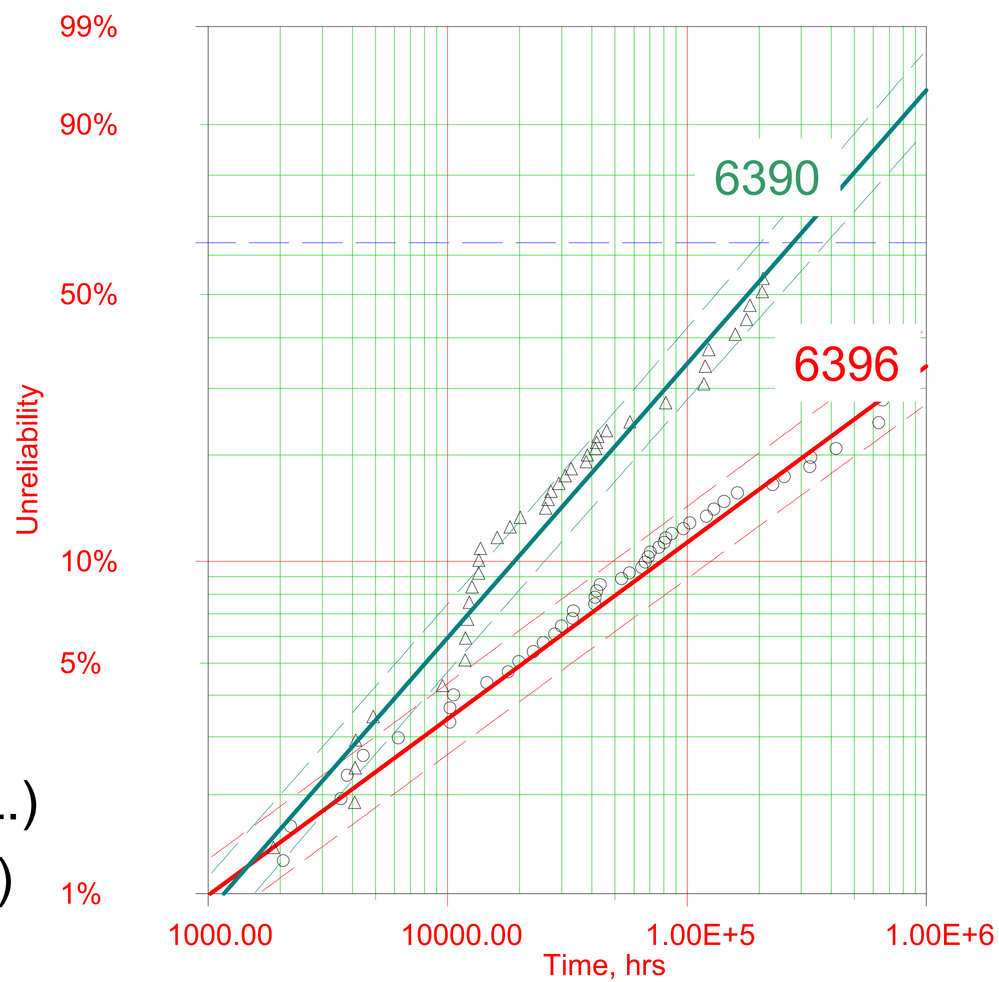
- 100μm wide aperture chip
  - 20W CW rollover power
- 105μm diameter, 0.2NA fiber
  - 8W rated power at 10A

6396 Chip Reliability Improvement

- MLE Results:

$$\beta = 0.54$$
$$E_A = 0.61eV$$
$$n = 2.7$$
$$\eta_{op} = 5.1 \cdot 10^6\ hrs$$

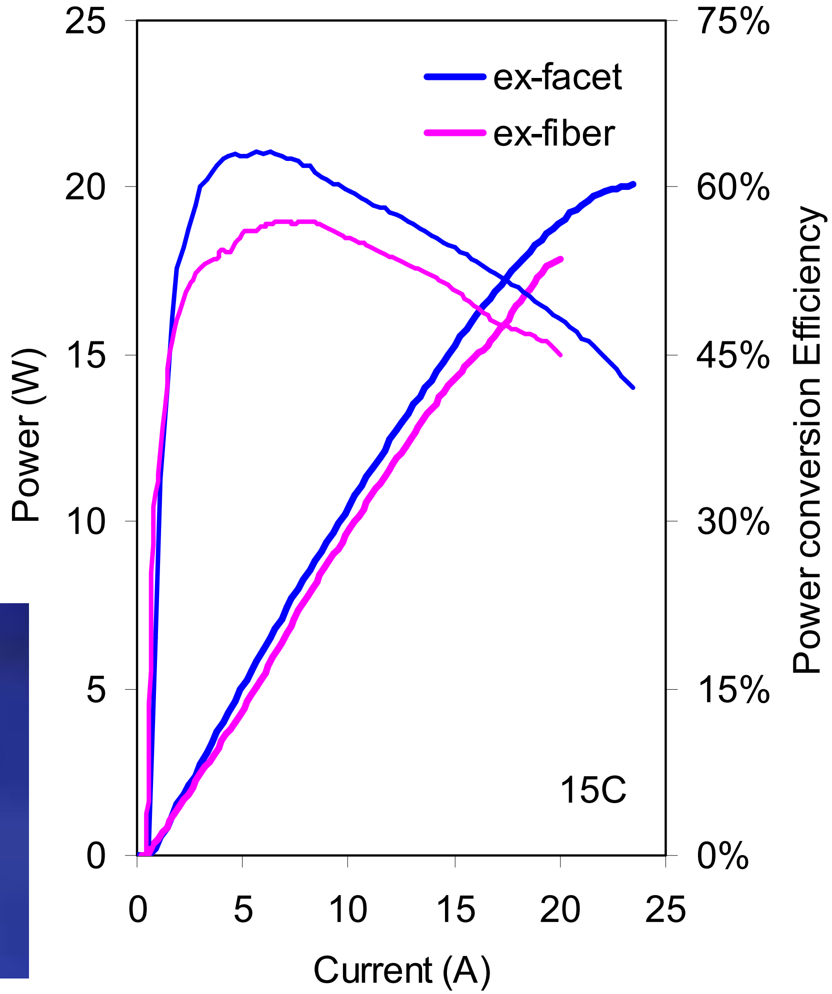
- Revised reliability:
  - P=8.0W
  - T_h=35C
  - Median time to failure =1,500,000 hrs (60% C.L.)
  - 6% F at 20khr (60% C.L.)



JDSU

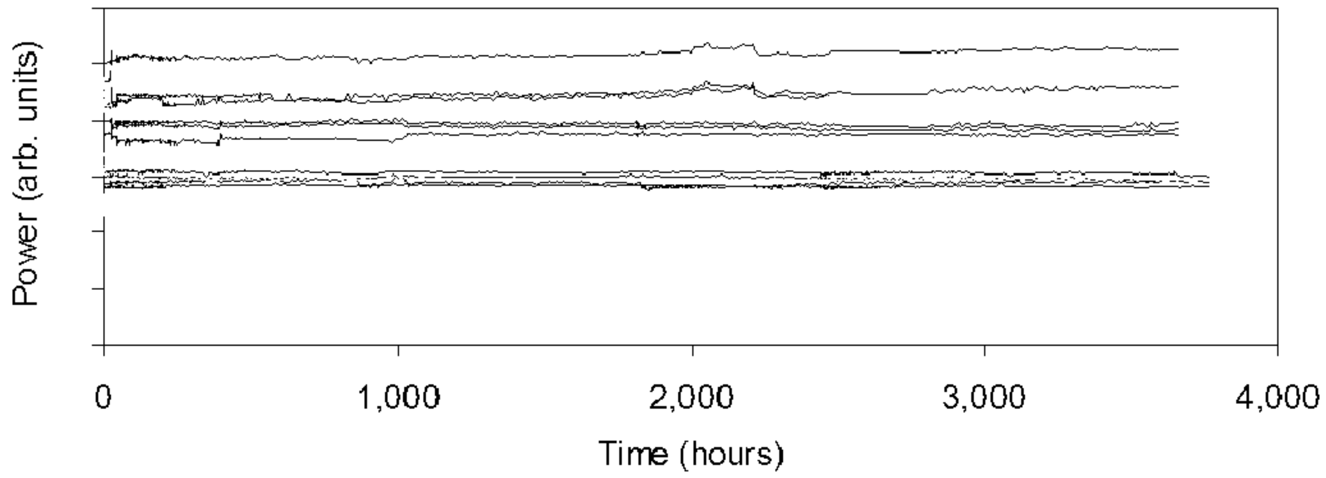
Example: JDSU L4 module performance & testing

- Laser chip
  - InAlGaAs
  - 880-1000nm
  - 100μm aperture
  - 4.1mm cavity
  - AuSn solder
- Fiber-coupled package
  - 105μm diameter
  - 0.15 or 0.22NA
  - R_{th} = 2.2°C/W
  - 10W rated power
  - 50% wall plug

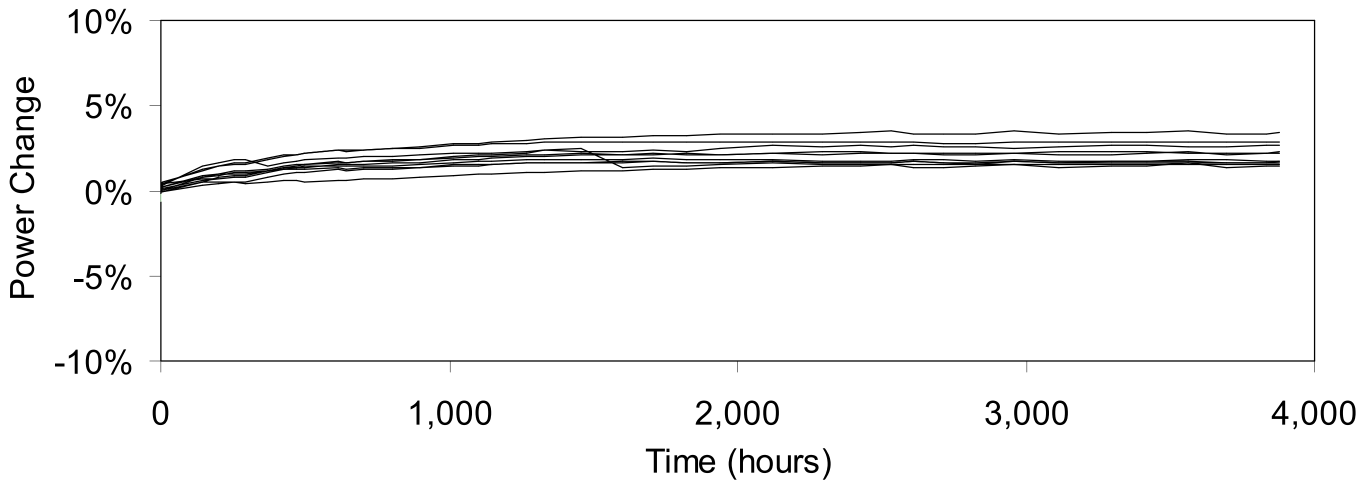


Accelerated life test examples

- Chip Life Test
  - 9.3W, 13A
  - T_{case} = 70°C
  - T_j = 117°C
  - 28 lasers
  - 0 failures

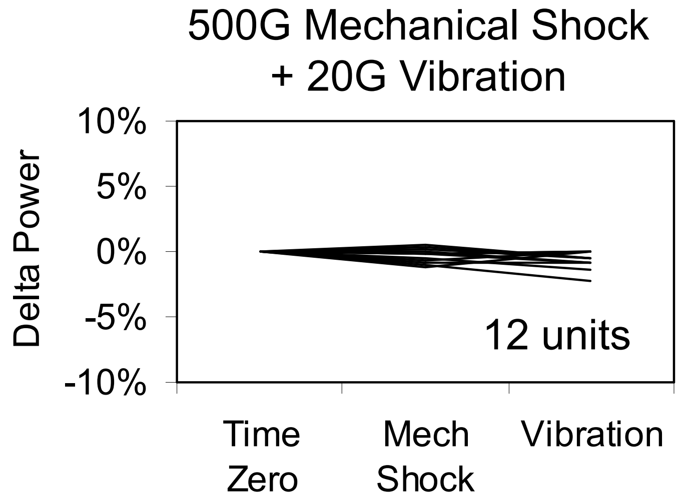


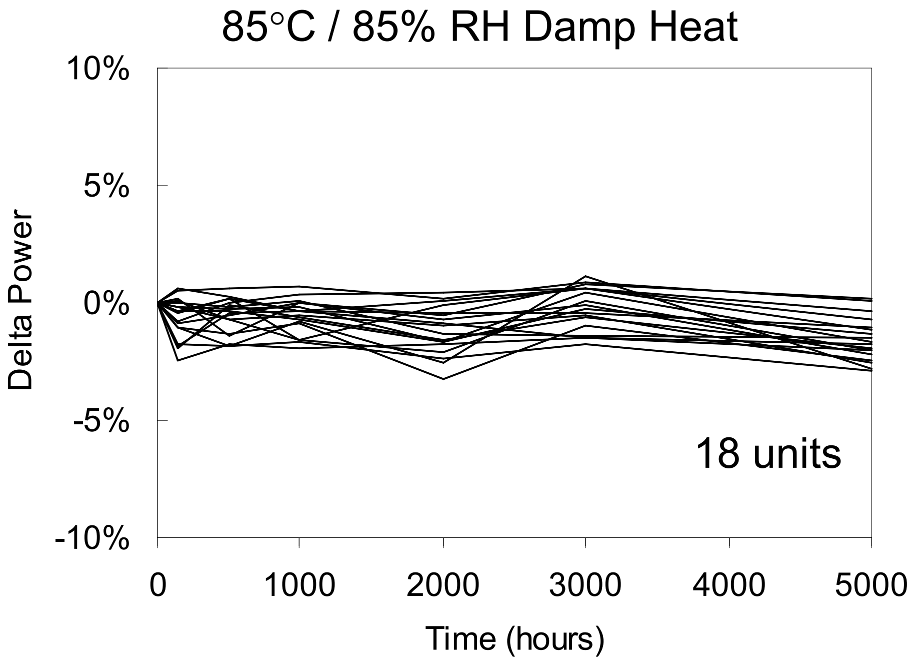
- Package Test
  - 10W, 12A
  - T_{case} = 35°C
  - 14 lasers
  - 0 failures

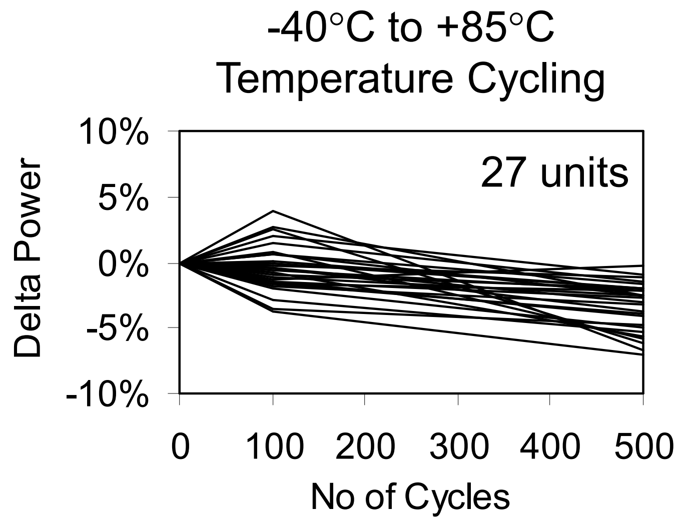


L4 Package qualification and robustness tests

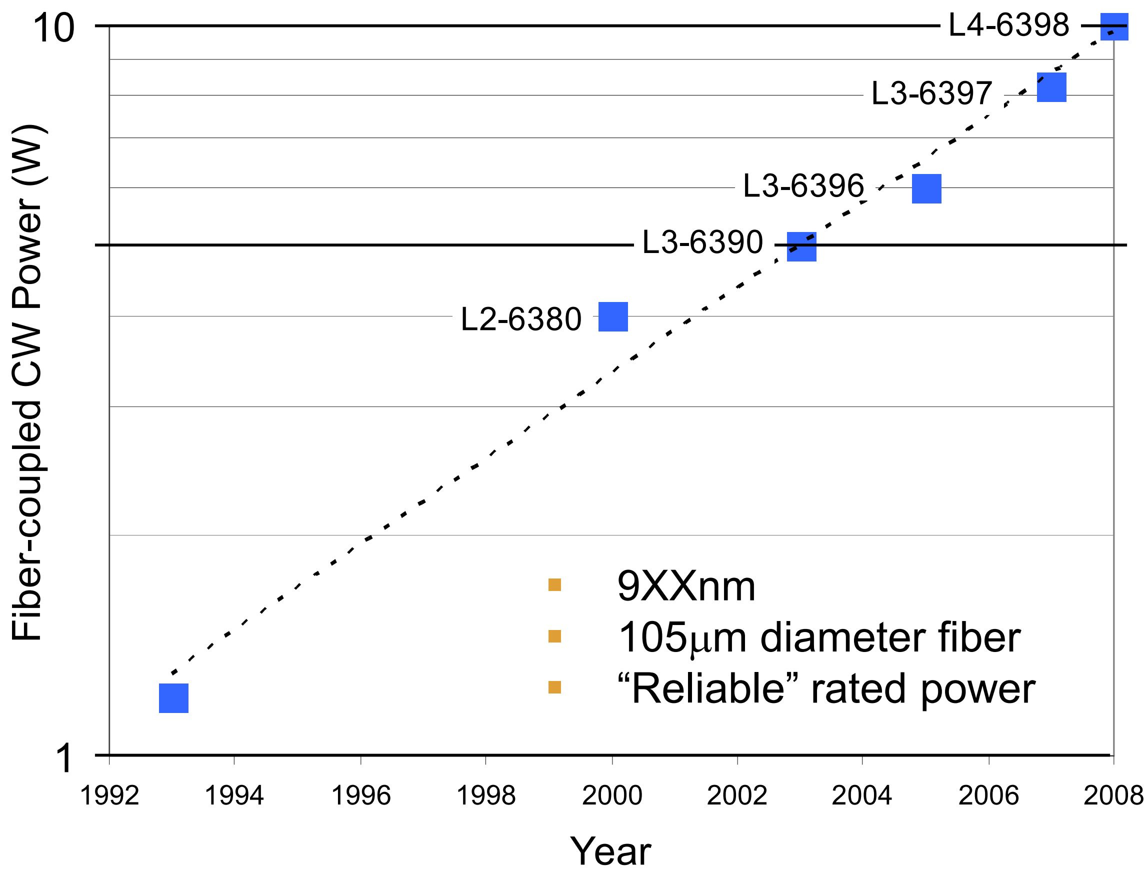
- Reference Telcordia GR-468
  - Zero package failures in full suite
  - Proves robustness of design





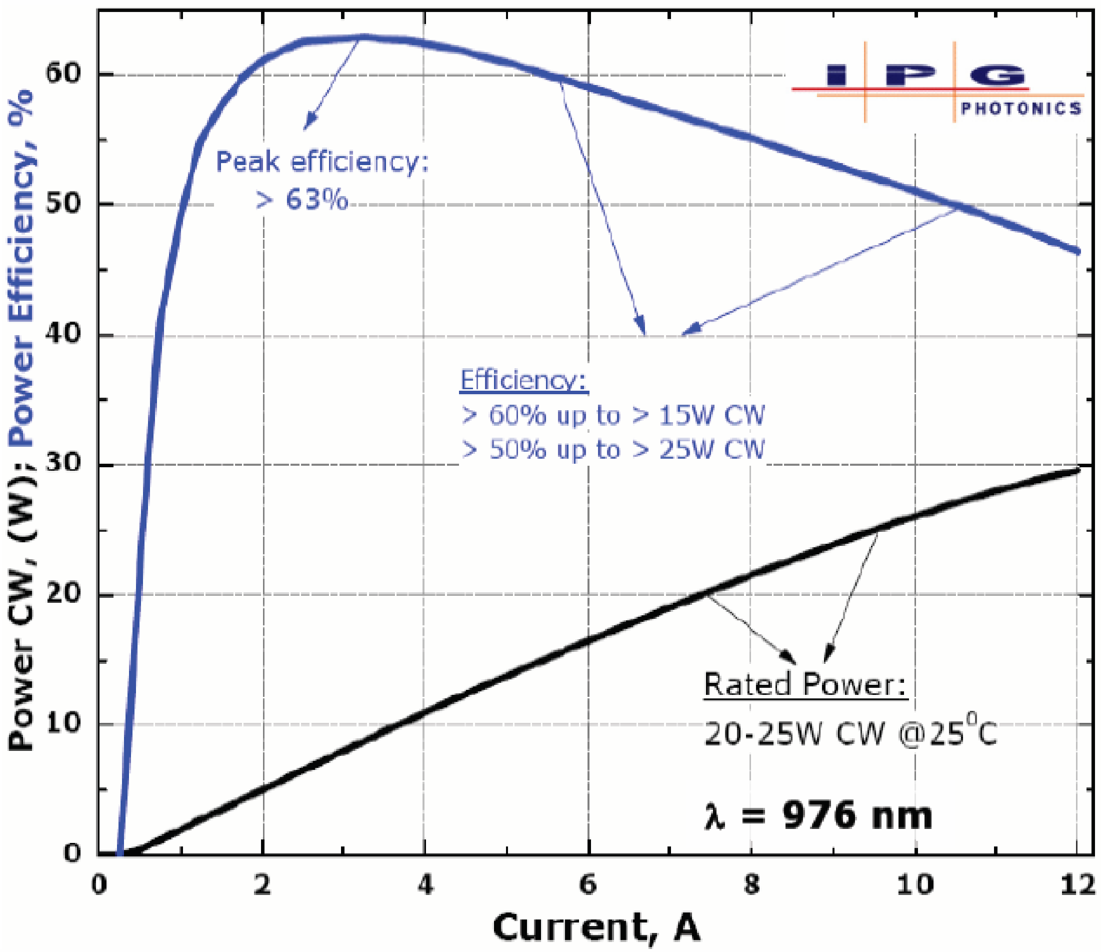


Pump power trends – commercially available



- 15% annual increase in reliable power
- Similar trend for
  - 8XXnm
  - Single mode lasers
  - Multi mode lasers
  - Bars

Example III: Fiber Coupled Devices of 2006 design:
PLD-20-9xx series based on L=3.0mm COS: Ø=100 μm fiber, NA < 0.12

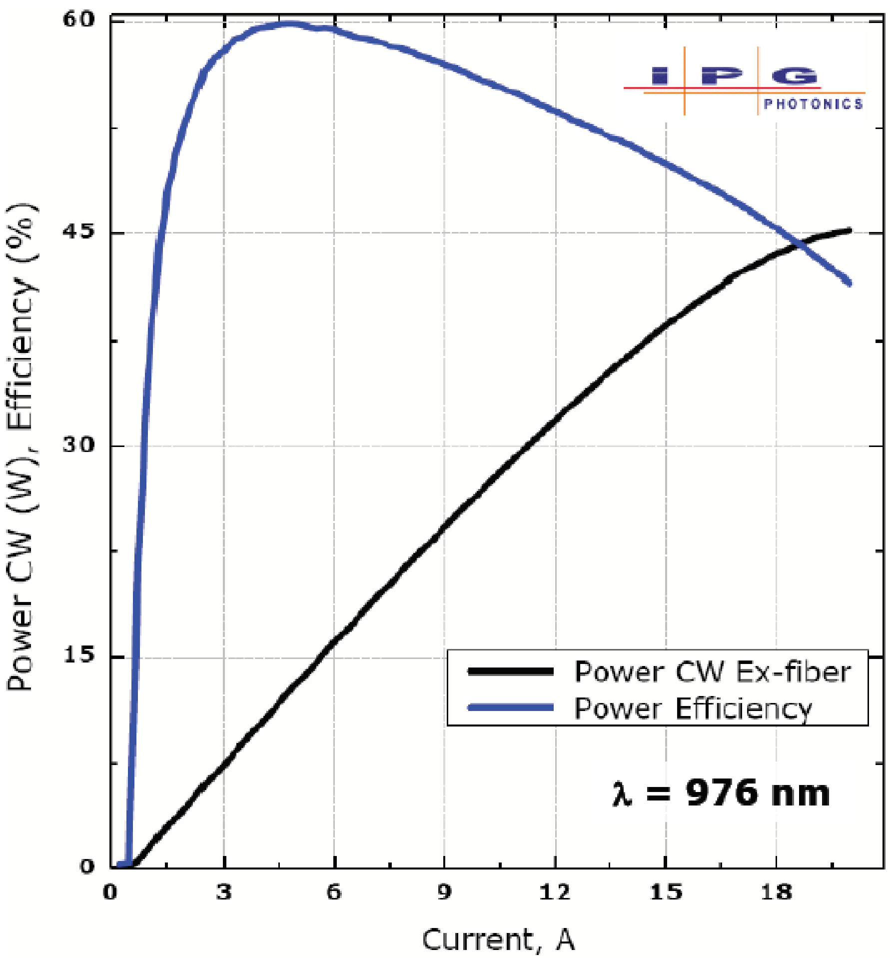


PLD-20-9xx pumps:
λ ~ 9xx nm; NA ~ 0.12
25°C heatsink temperature
(CE > 90%)

Hermetically sealed package requires simple water or air cooling

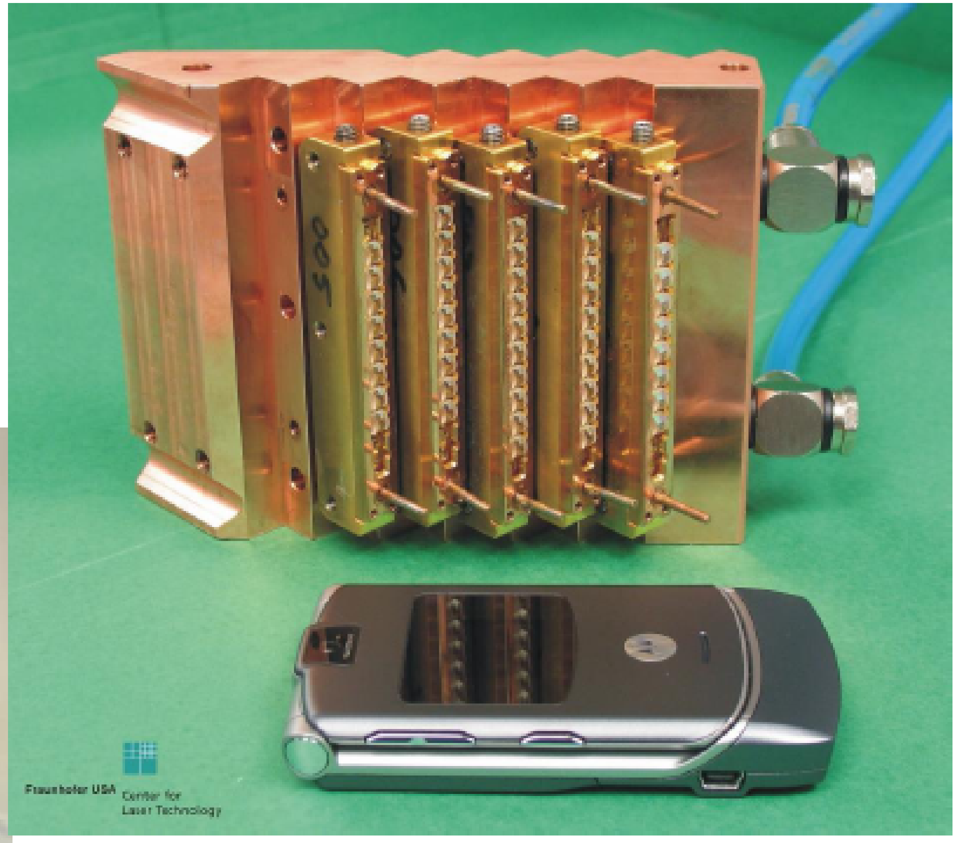
Example IV: Fiber Coupled Devices of 2008 design:

PLD-30-9xx series (based on L=4.5mm COS): Ø=100 μm fiber , NA < 0.12



- Single emitter-based technology ensures high reliability of the pumps
- High fiber coupling efficiency (>90%) ensures industry highest power, brightness and power efficiency

2D Single Emitter Arrays for Ultra High Brightness Diode Laser



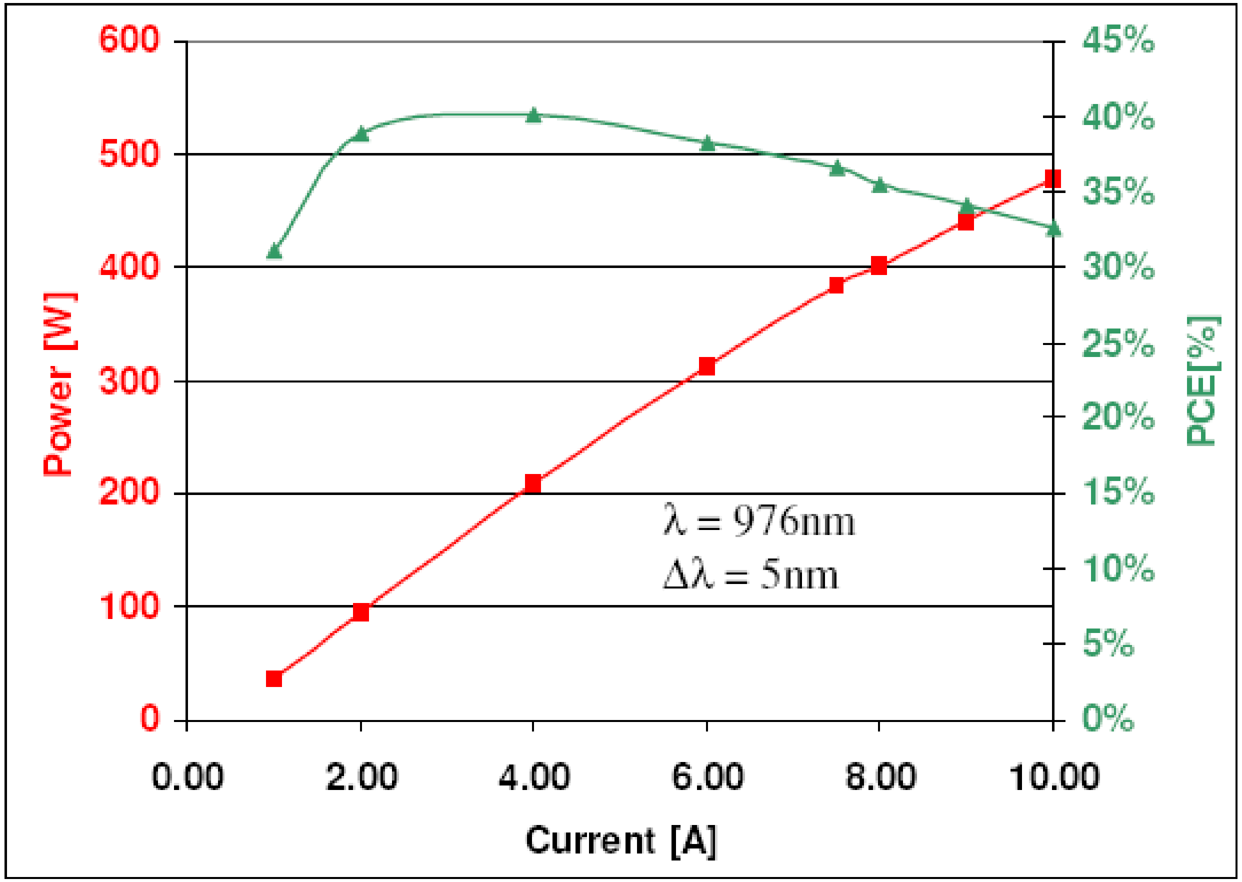
Fraunhofer USA Center for Laser Technology

visotek inc.
smart laser tools

Results of Ultra High Brightness Diode Laser

Products

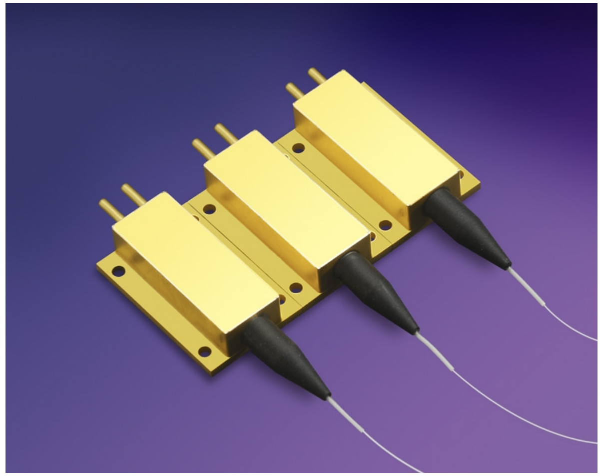
- ➢100W / 100µm / 0.2
- ➢400W / 200µm / 0.2



Fraunhofer USA Center for Laser Technology

visotek inc. smart laser tools

Example I: Second-Generation Fiber Pump Modules

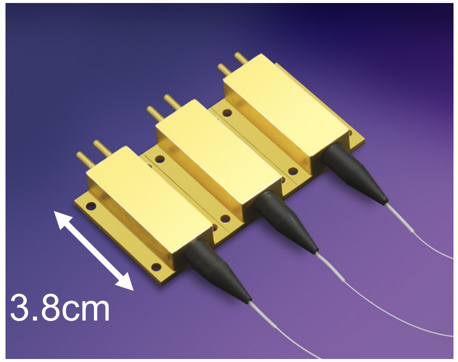


- **Characteristics**
  - Multiple emitters (e.g., a single mini-bar)
  - Micro-optics for beam conditioning
  - More power in (e.g., higher current at std voltage)
- **Features**
  - Enhanced brightness per fiber channel
  - Reduced thermal and electrical resistance (higher power at rollover)
  - CoS with single-emitter economies, no smile
  - Independent dropouts, reduced facet loading, enhance reliability
  - Highly scalable at module level

Mini-Bar Fiber Pump Module

- **Brightness of industrial modules now exceeds 1 MW/cm²-sr**

e.g., Orion™ series

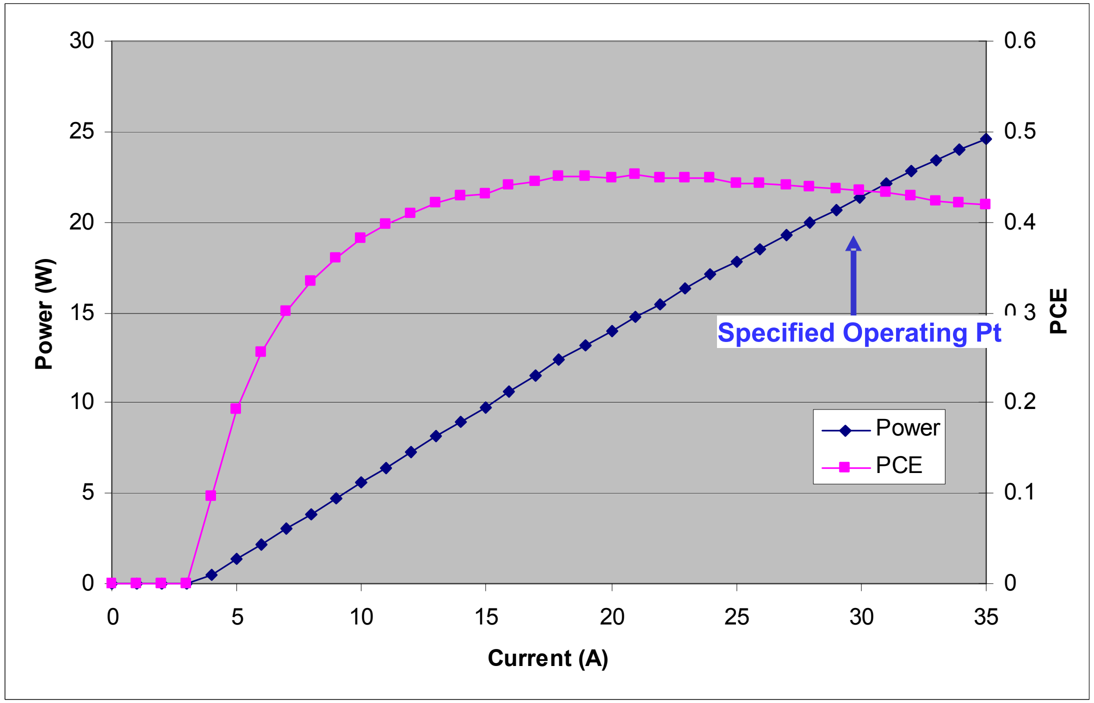


- 20W, 105um core, 0.20NA

- 915nm, 940nm, 976nm

- mini-bar architecture

- very high reliability

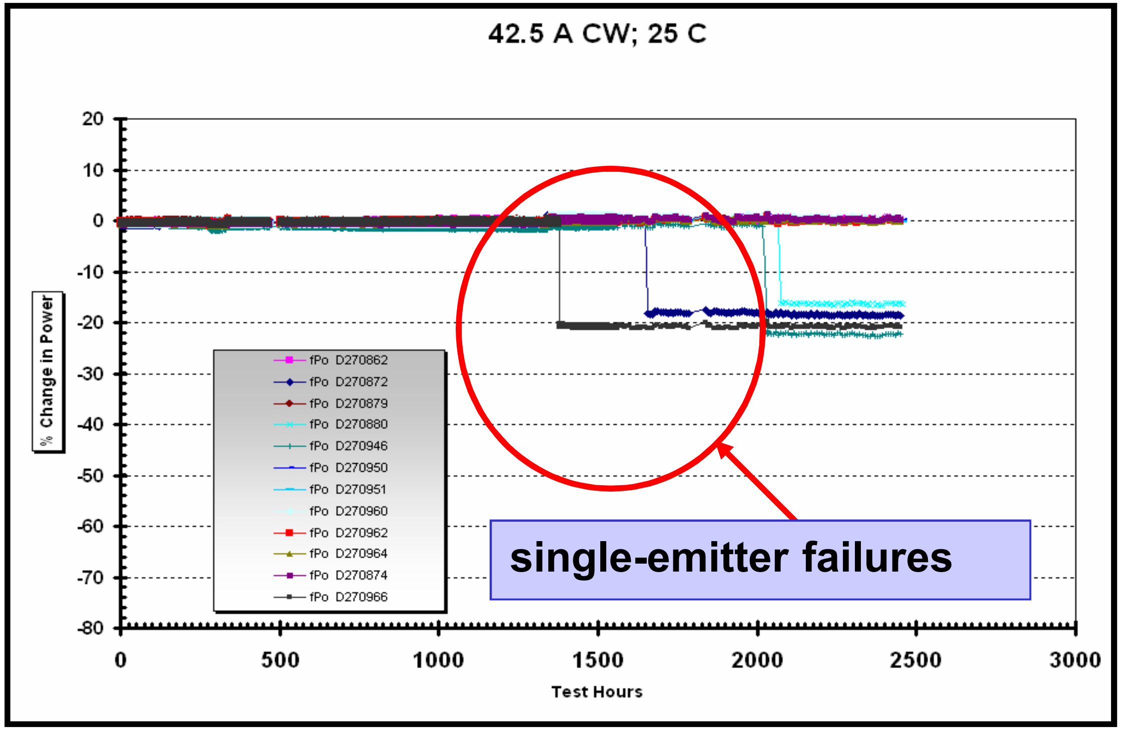


Newport Experience | Solutions
Spectra-Physics A Division of Newport Corporation
H2 short presentation

Mini-Bar Reliability: verification of emitter independence

CoS: 5-element mini-bar on CT

(AuSn solder on CuW heatsink)



Multi-Stripe Modules as Ensembles of Semi-Independent Emitters:

- failures are dominated by random, sudden failures of individual emitters
- the failure of an individual emitter only impacts other emitters by an increase in ensemble drive current (for constant power) and warming of the other stripes on the same mini-bar
- all assumptions are consistent with test data giving over 300,000 hrs MTBEF (mean time between emitter failure) at the specified operating point

Fiber combiner
Fused and Proximity

Fused: (6+1)*1

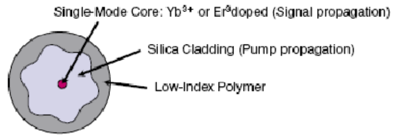


Figure 2 Cross-section of double-clad optical fiber for cladding pumping.

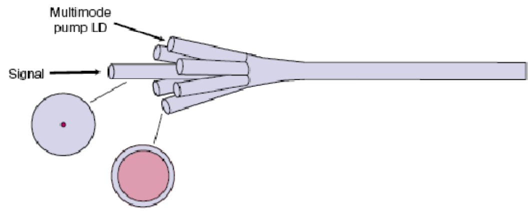
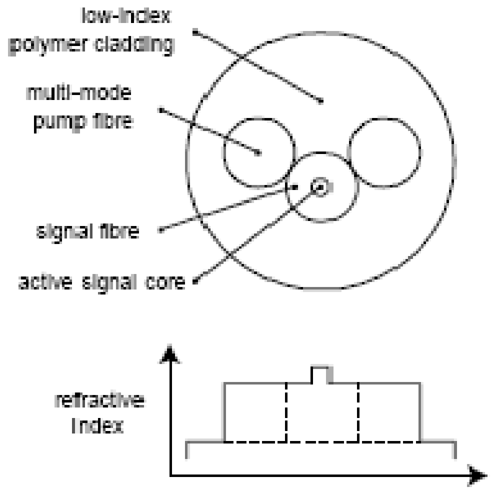


Figure 3 Schematic of tapered fiber bundle.

	Fiber	NA
Signal input	HI 1060	
Pump Ports	6*105um	0.22
Output	20um/400um	0.06/0.46

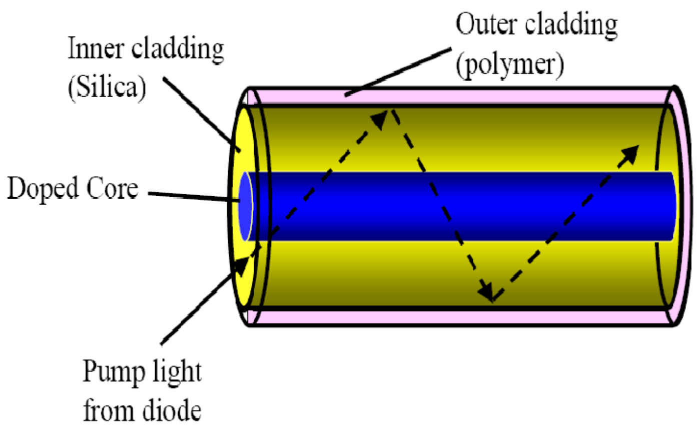
Proximity: (2+1)*1

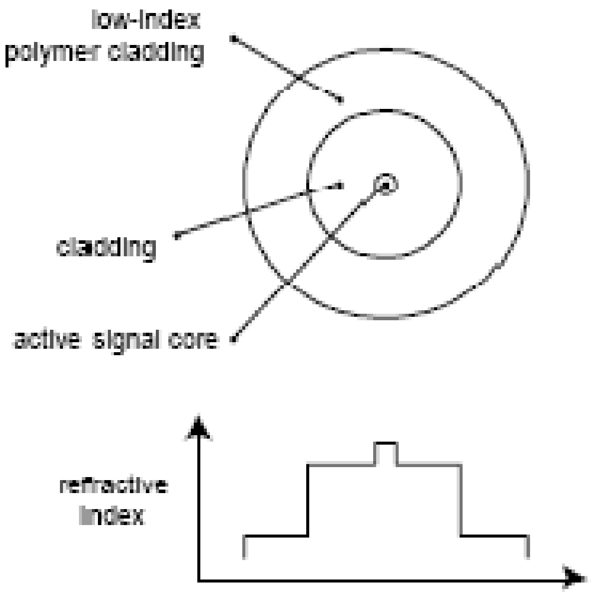


Fused can be extended to beyond 20 inputs
Proximity needs high brightness pumps

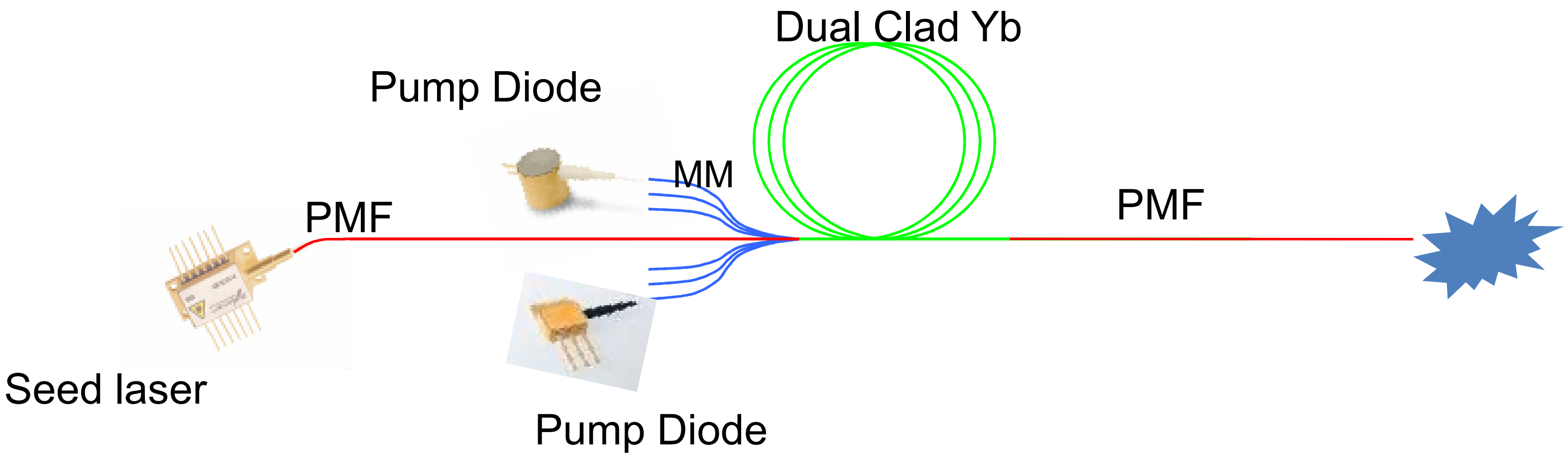
Pump power injection
Coaxial dual cladding

Coaxial cladding
400um, NA=0.46: 150’000 modes





Fiber Laser: MOPA

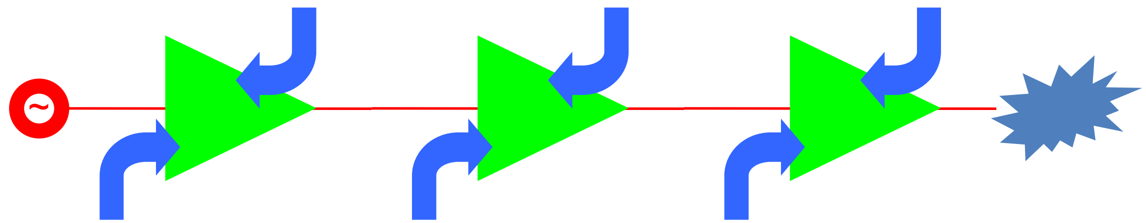


- Seed laser
  - Fiber laser: Good spectral control
    - Need external modulators (Pockels Cell)
  - Diode laser: Excellent dynamic control
    - FP laser have poor spectral control, of no concern
    - DFB have excellent spectral and dynamic control

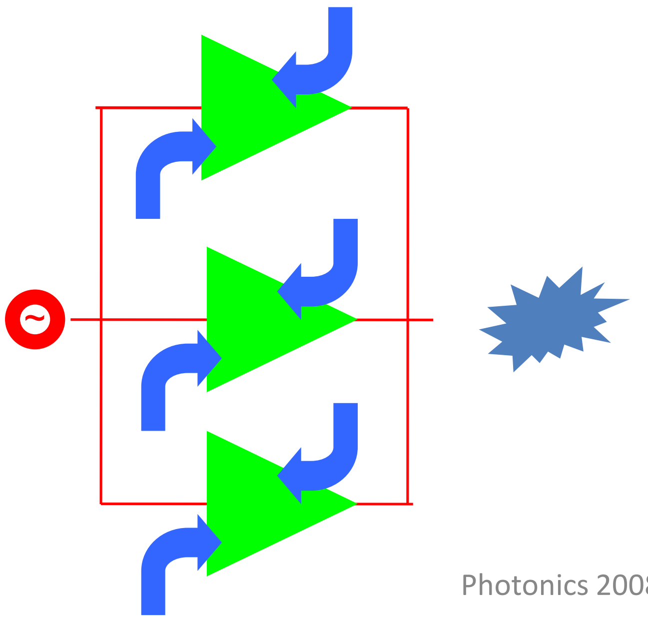
- Pumplaser
  - High Brightness: Single emitter broad area 9xxnm MM diode

Scalability of Fiber Laser

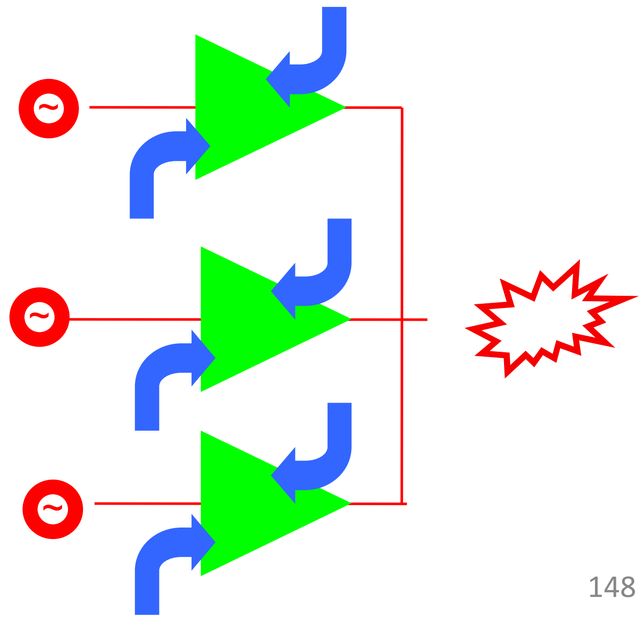
- Serial



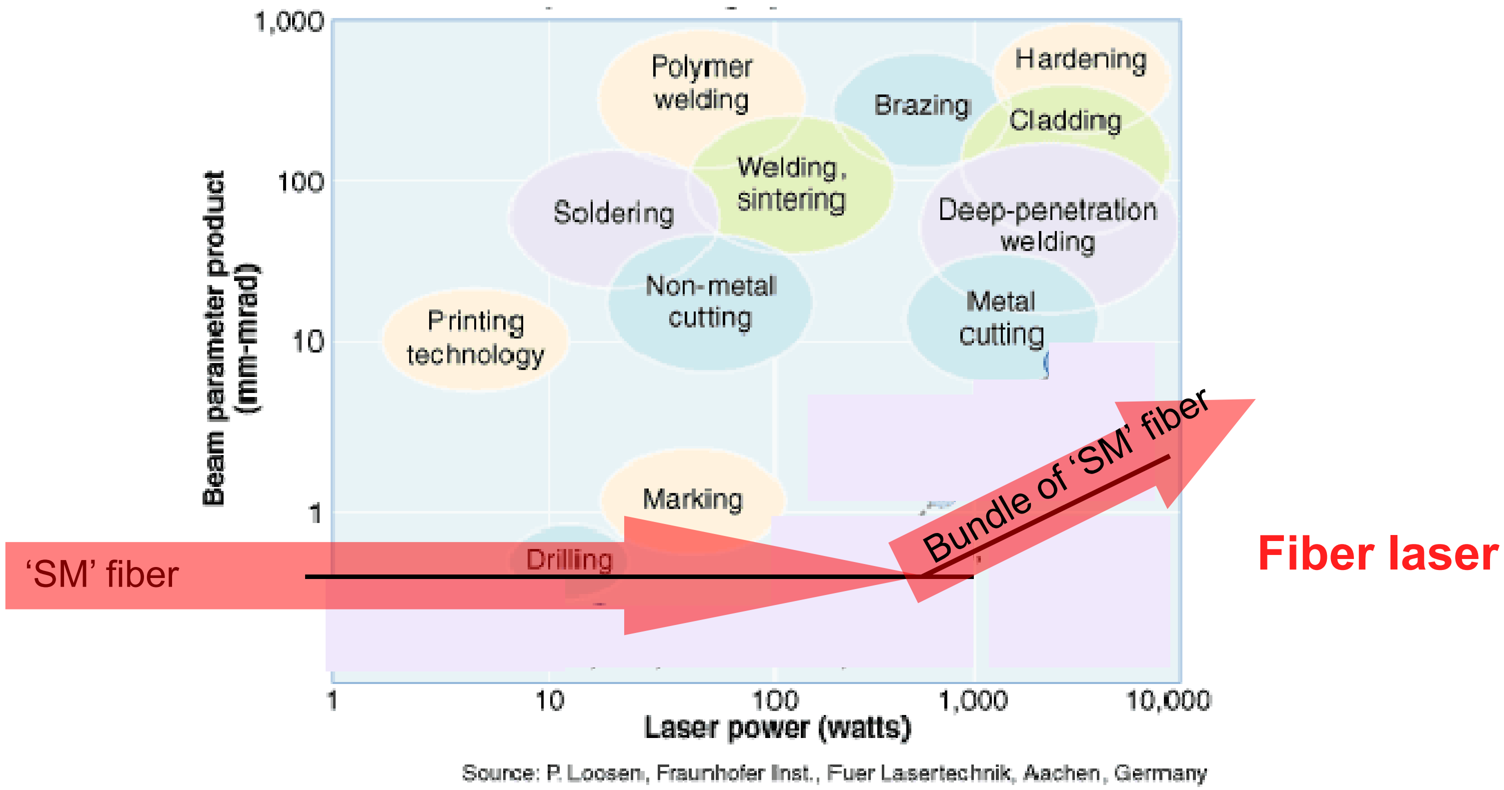
- Parallel
  - Coherent



Incoherent



Power Photonics: Fiber Laser
Fiber Delivered Beam Machining Tool

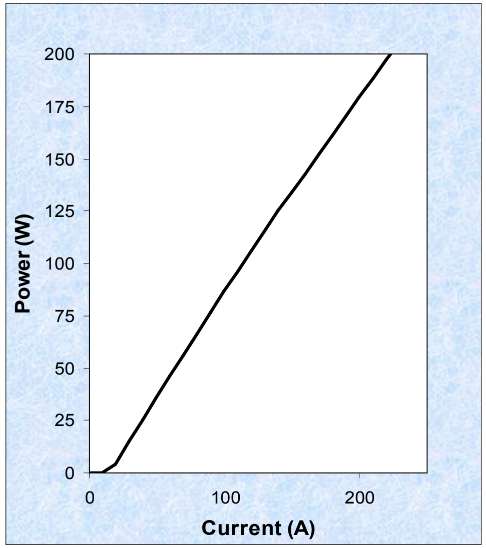


- Solid State
  - Hermetically sealed Diodes coupled to Fibers
  - Fiber delivery
- Technology
  - Apply telecom technology to power photonics

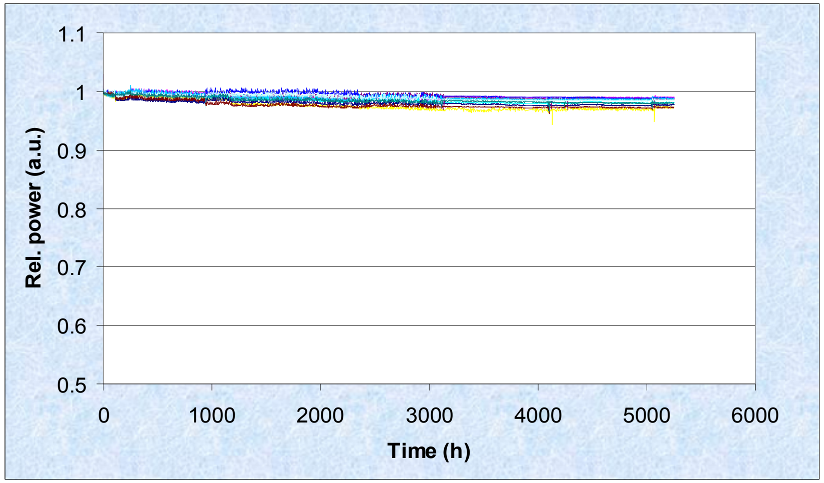
9xxnm 120W Bar Performance

- Electro-Optical
  - Power: 120W @ 140A
  - Threshold: 14A
  - Slope Eff.: 1W/A
- Reliability
  - 5’200h at 120W lifetest data at 1.33Hz full on/off pulsed conditions available
  - The extrapolated median lifetime is above 80’000hrs or 350 MShots, less than 1% fails after 120 MShots.
  - No open fails

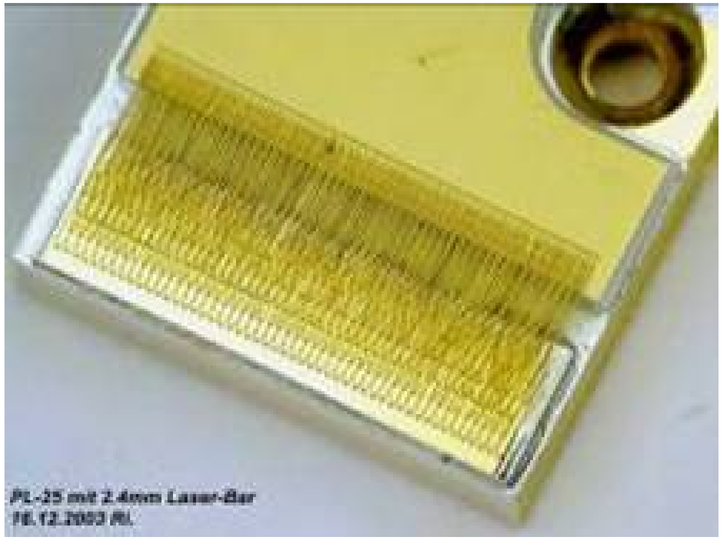
P-I curve at 25C up to 200W:

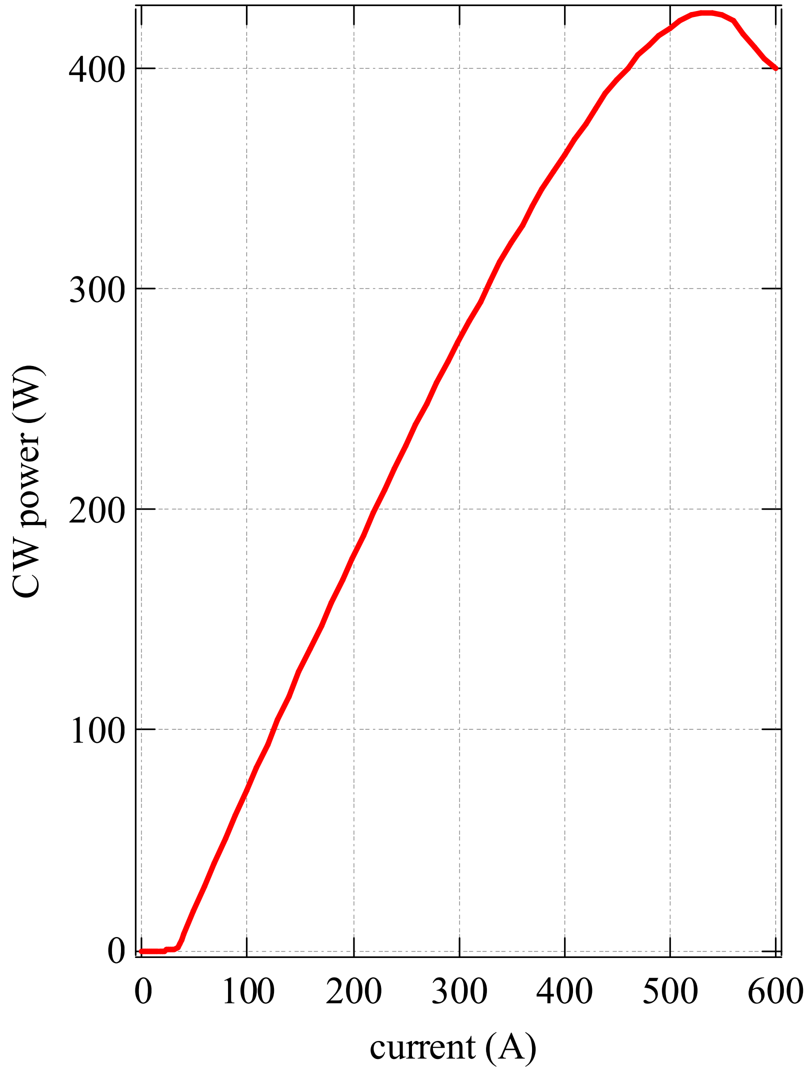


Condition 120W pulsed (1.33Hz, 0<->140A)



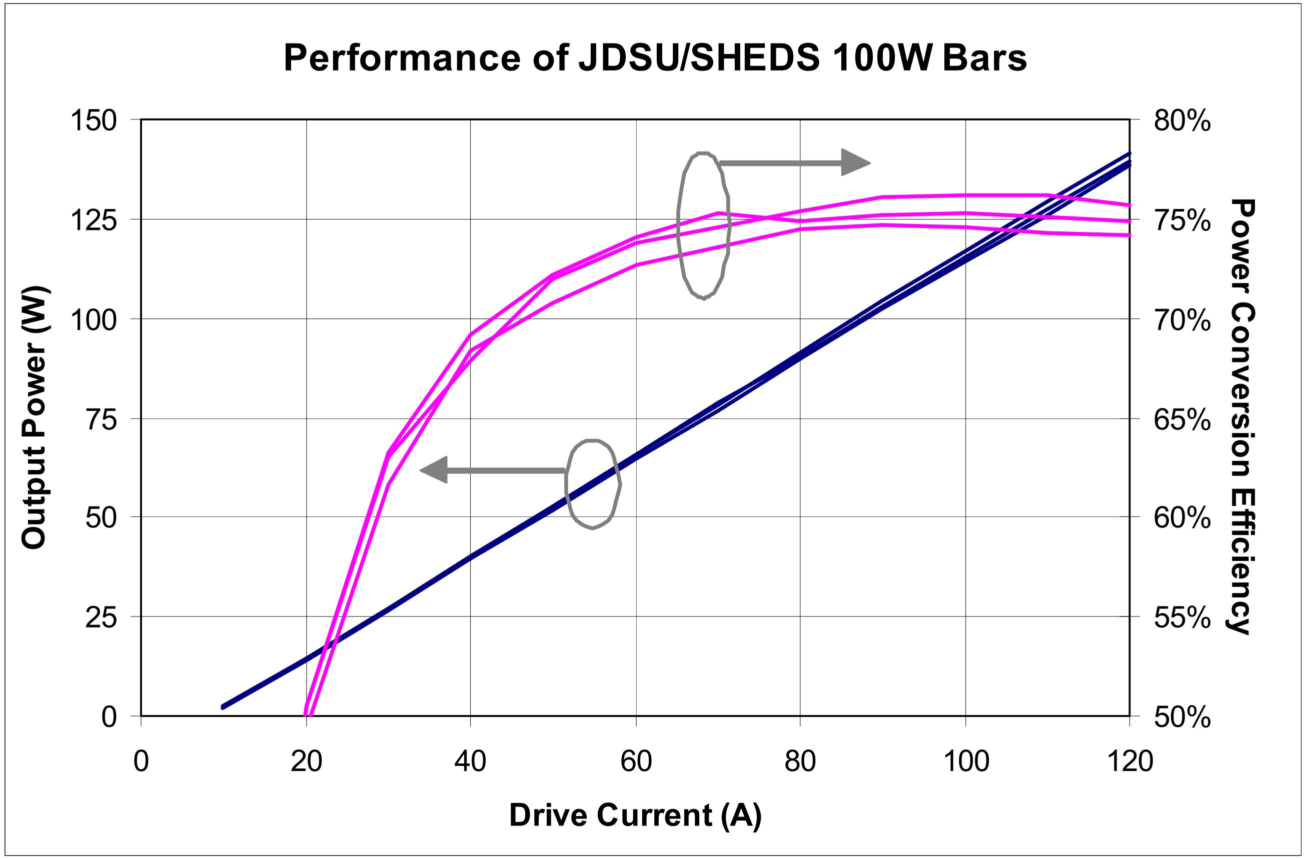
Bar with 425W CW at 980nm





– 425W at 980nm, 1cm, 50% FF
– On standard MCC
– 3.6mm long laser cavity

High-efficiency bars



- >75% wall plug efficiency from 120W 940nm bar (SHEDS design)

Results – Compare FF = 50% to FF = 33%

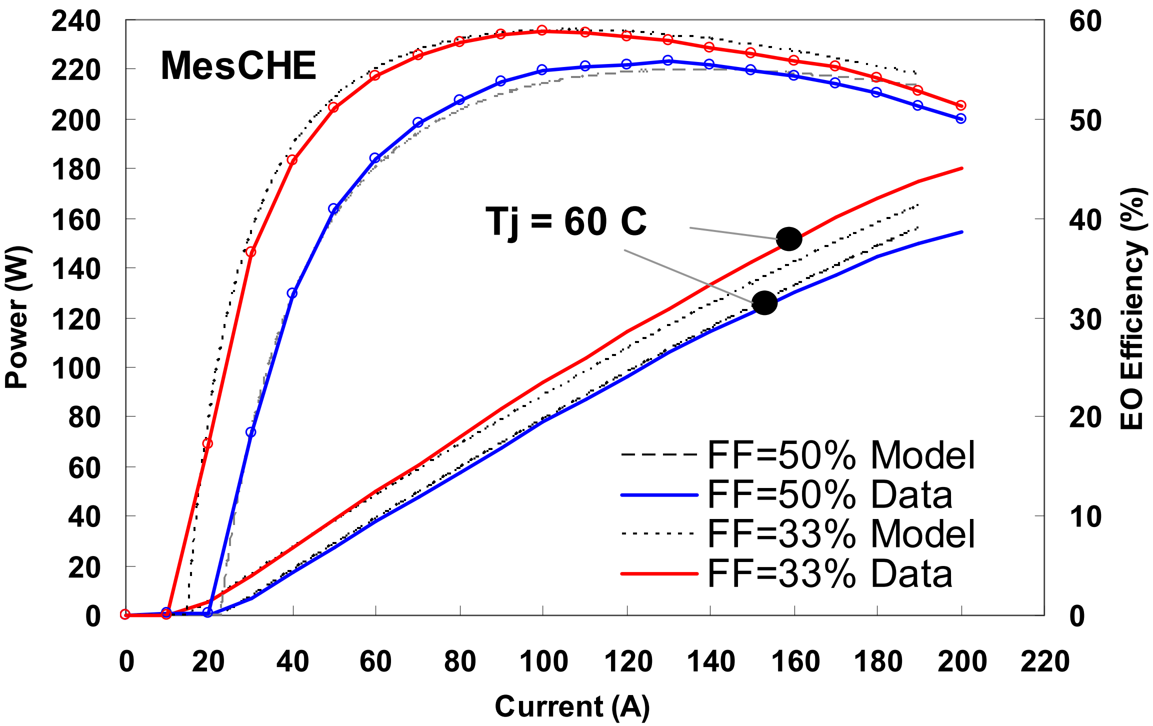
- Mesochannel Compact Heat Exchanger (MesCHE)

R_{th} = 0.38 C/W

L = 3.5 mm

P = 127 W (FF=50%)

P = 151 W (FF=33%)



TRUMPF

Results – Compare FF = 50% to FF = 33%

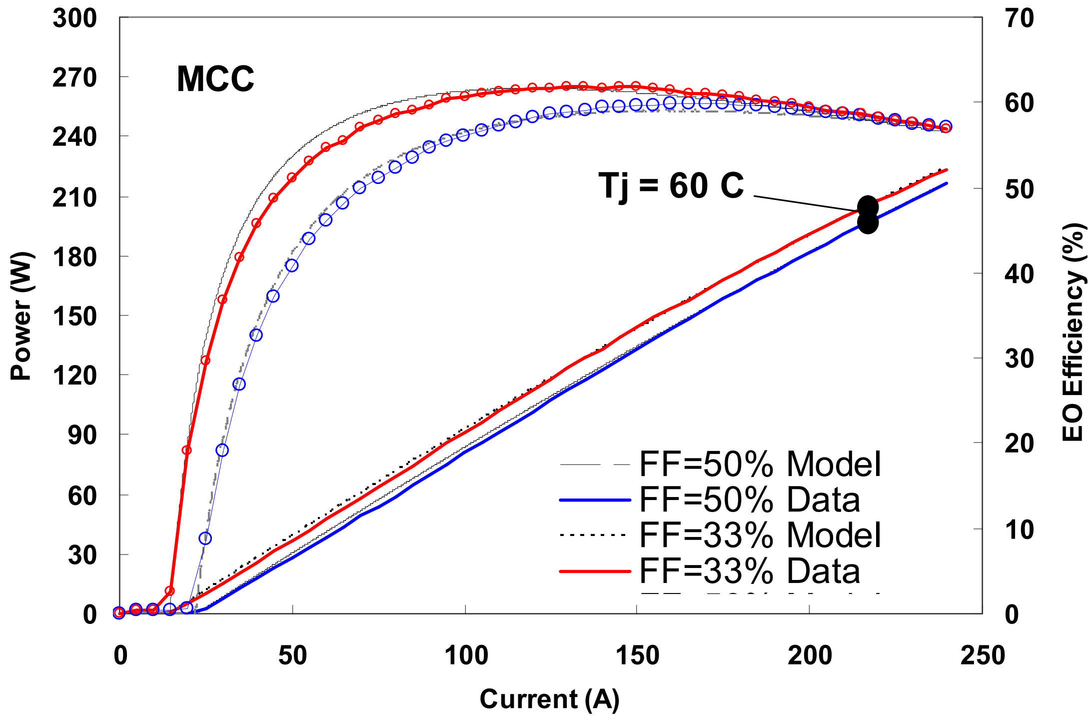
- Microchannel Cooler (MCC)

R_{th} = 0.23 C/W

L = 3.5 mm

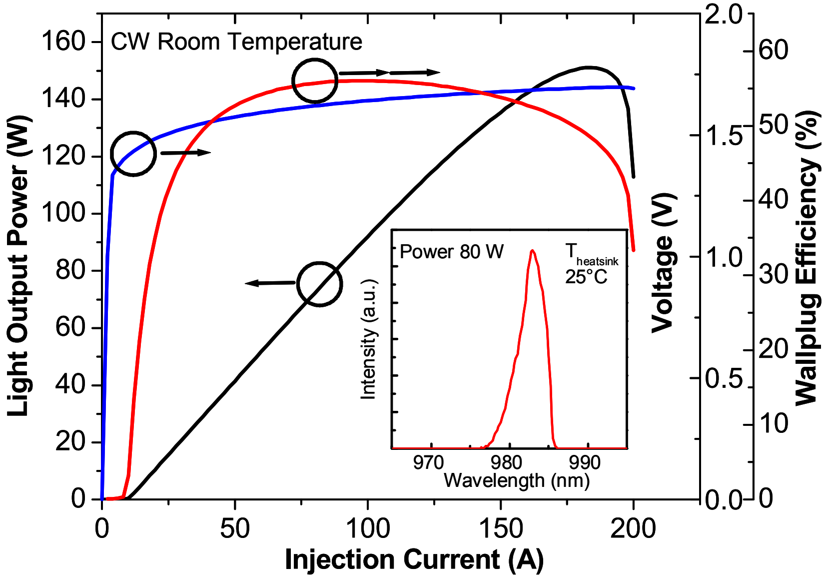
P = 200 W (FF=50%)

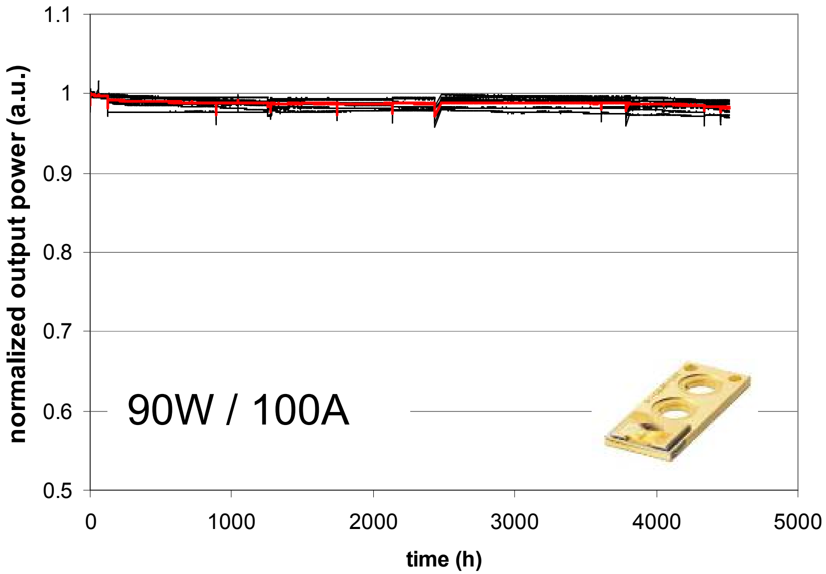
P = 207 W (FF=33%)



AHPSL 2008 Seminar #1

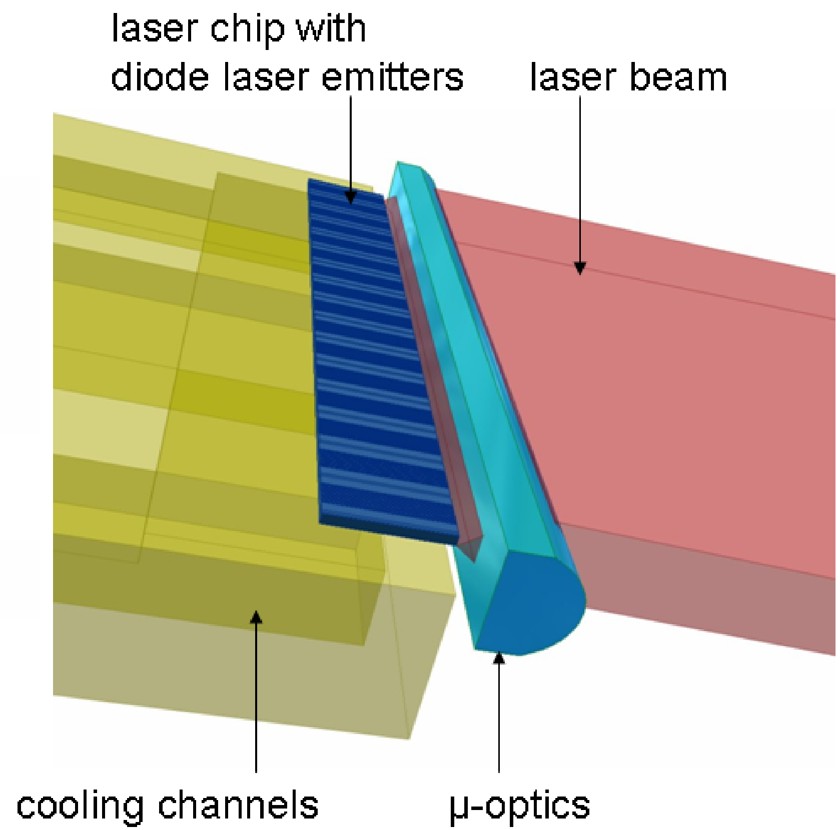
Reducing Complexity: 9xx 1/3 size VHB Bar





- Reduced 1/3 size BAR on MCC
  - Significant reduction on complexity of high power systems due to high total power from actively cooled MCC
  - Maintain drive currents below 100A at increased brightness (bar size)
    - Efficiency >55%, smile 1um, lat. farfield 8° (90% power)
  - Highly reliable operation (hard pulse 1.3 Hz, 50% duty cycle, full ON-OFF)
    - Power wear-out <1% / 1000h

Challenges for the design of HPL: Bar Bonding – Low Smile and High Current Capability

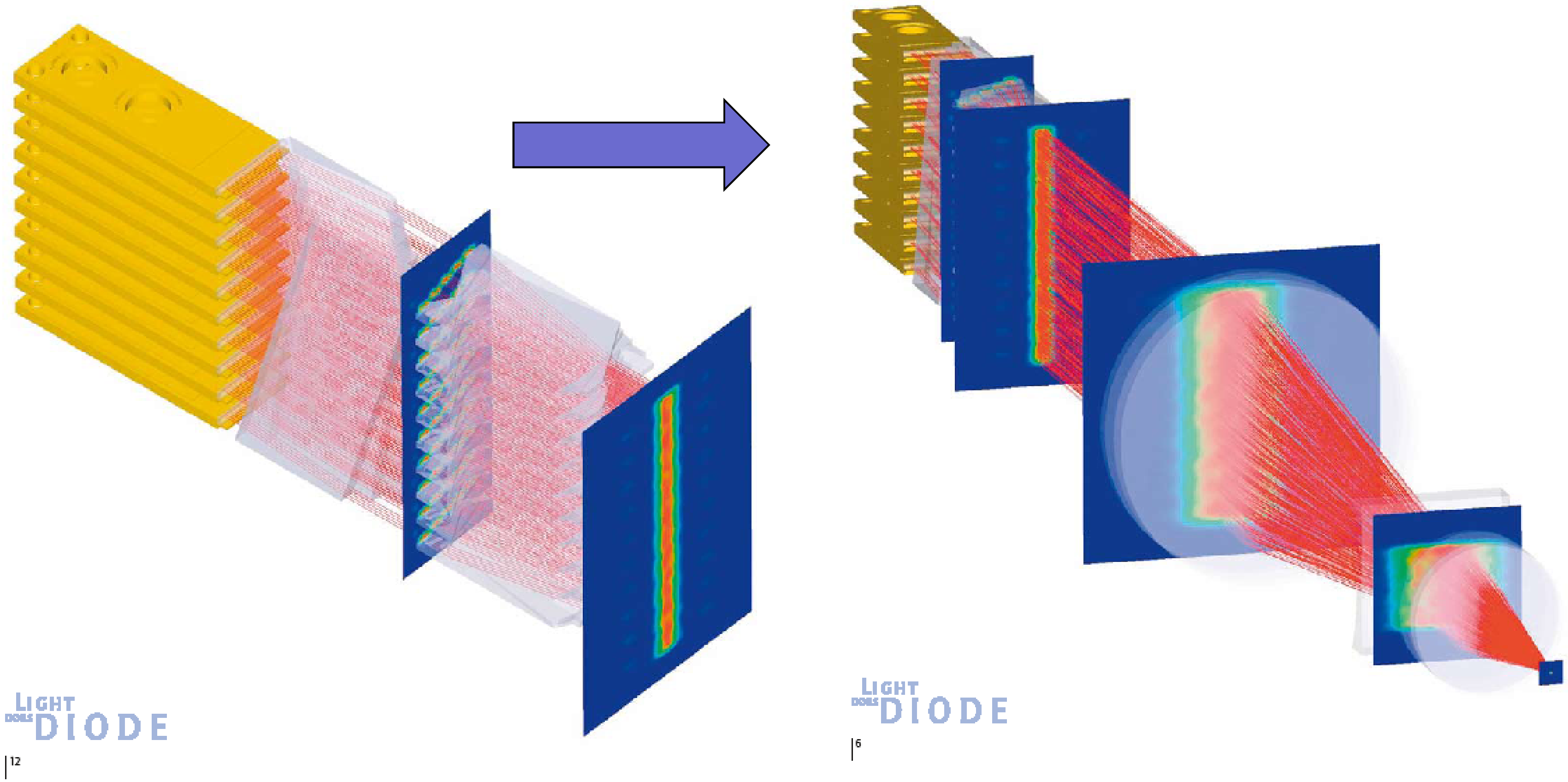


Subsystem design

- Submount material (expansion matched)
- Robust cooler design (avoid corrosion)
- Strain – Stress (reduced at all interfaces)
- low Smile (hard solder, low smile)
- Passive optics design (efficient)
- Fiber diameter (low core, low NA)

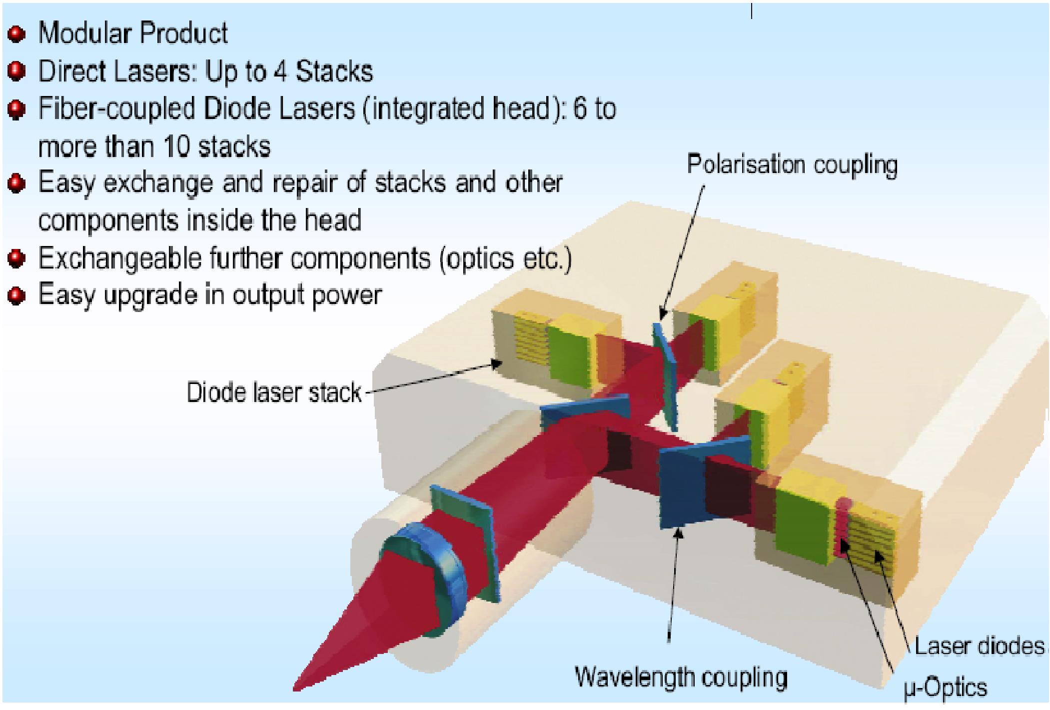
Picture with courtesy of laserline

Bar multiplexing to achieve highest optical power densities for direct application



Picture with courtesy of laserline

Wavelength division multiplexing



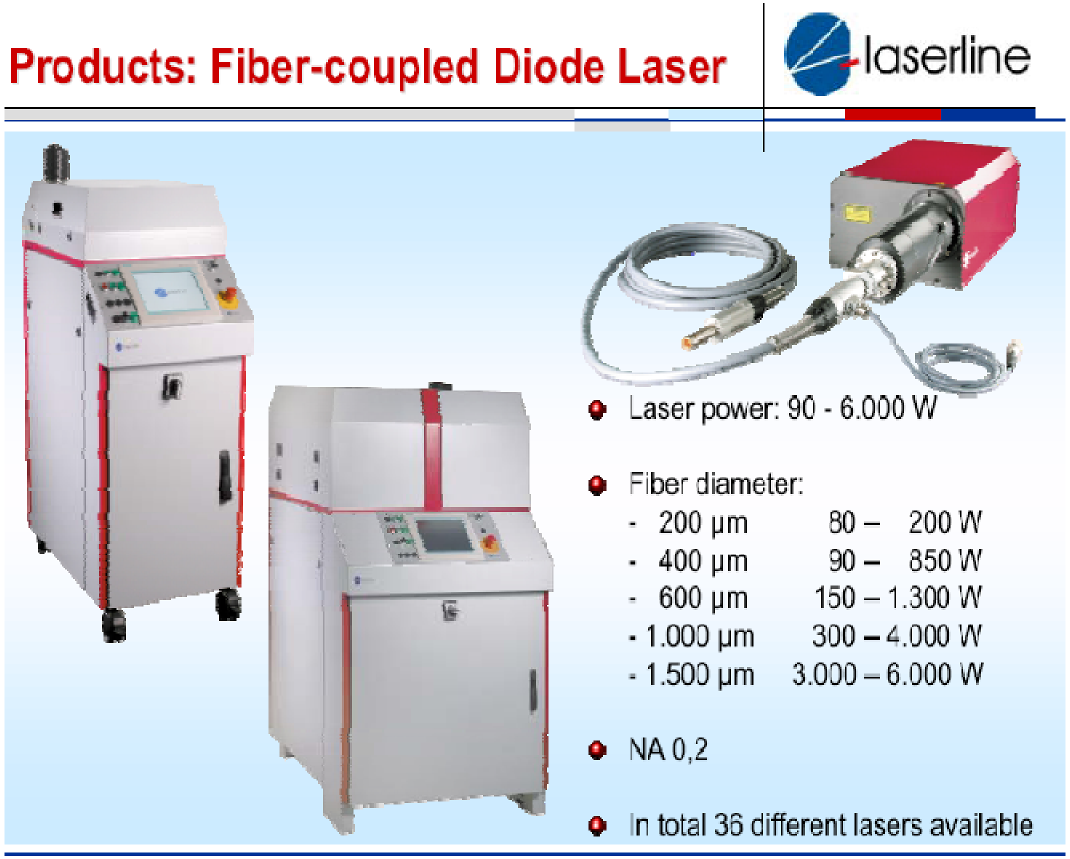
Laserline GmbH, Germany

High Power Single Mode Laser Diode

EDFA: Killer application: Done and dusted

used now for printing

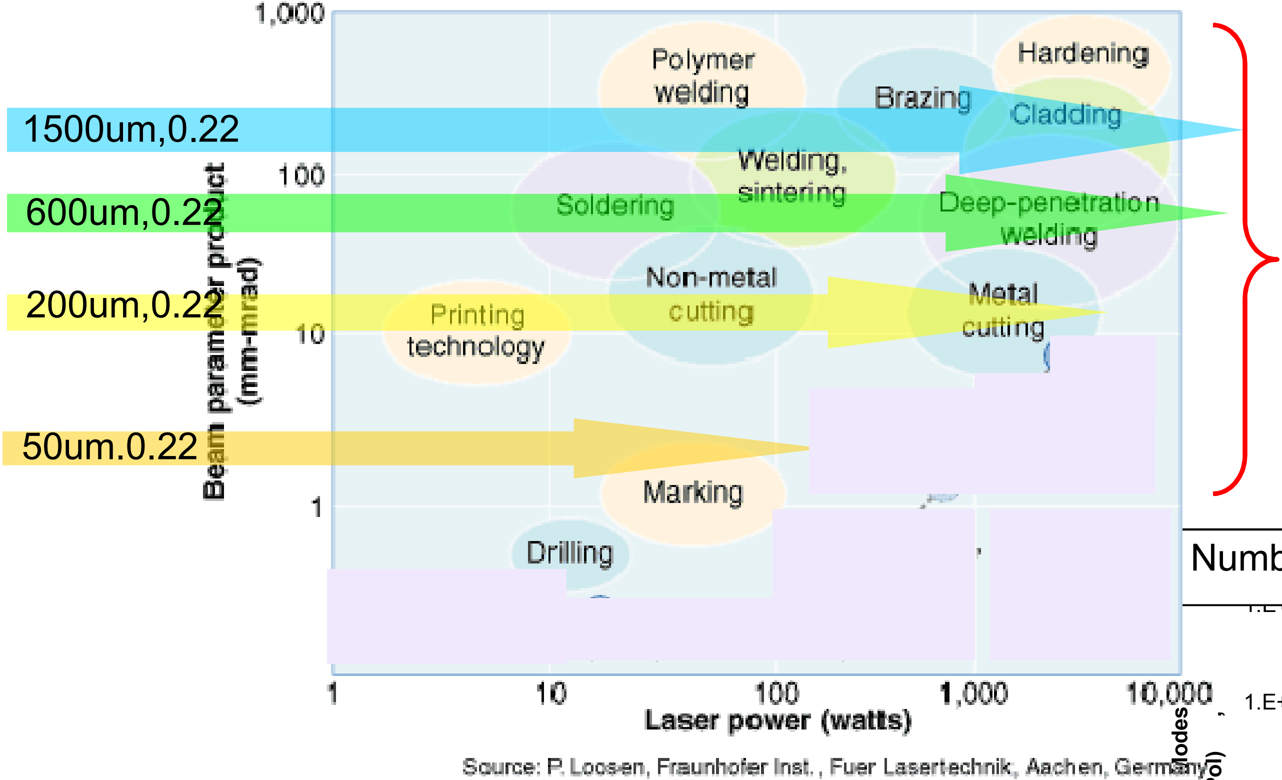
Direct Coupled Diodes:

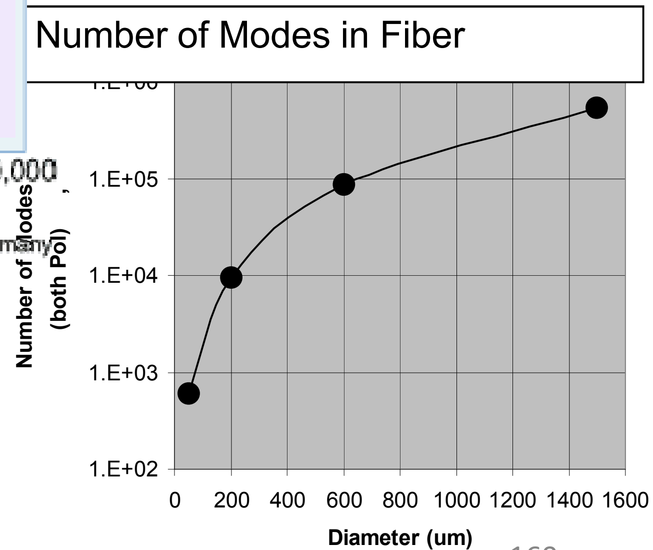


Laserline GmbH, Germany

- Practical limits to radiance?

9xxnm Multimode Pump Diodes: Machining directly with Pump Diodes





- Single Mode Pump Diode: 1W
- Multimode Pump Diode: 0.5W/mode
  - Low cost packaging needed

About the author

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- **Professional Summary**

  Dr. Christoph Harder has received the Electrical Engineering Diploma from the ETH in 1979, Zurich, Switzerland and the Master and PhD in Electrical Engineering in 1980 and 1983 from Caltech, Pasadena, USA. Christoph is co-founder of the IBM Zurich Laser Diode Enterprise which pioneered, among other laser diodes, the first 980nm high power pump laser for telecom optical amplifiers. It is estimated that today more than 50% of the internet links (including intercontinental communication) are powered up by such laser diodes, either manufactured in Zurich (majority) or by licensed partners.

  Christoph has been managing during the last few years the high power laser diode R&D effort in Zurich expanding, working closely with a multitude of customers, the product range into 14xx pumps as well as 808 and 9xx multimode pumps for industrial applications. Dr. Harder has published more than 100 papers and 20 patents and has held a variety of staff and management positions at ETH, Caltech, IBM, Uniphase, JDS Uniphase, Nortel and Bookham.

  Dr. Harder was General Chair of the International Semiconductor Laser Conference and the LEOS Annual Meeting, was on the board of IEEE/LEOS and has served on numerous technical program and steering committees. Today he is active on the board of OSA, BHL, President of Swisslaser.net and on the direction committee of NCCR QP.