"Direct Diode": History, Trends and Limits of Power Photonics

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Engelberg Lectures, 2009

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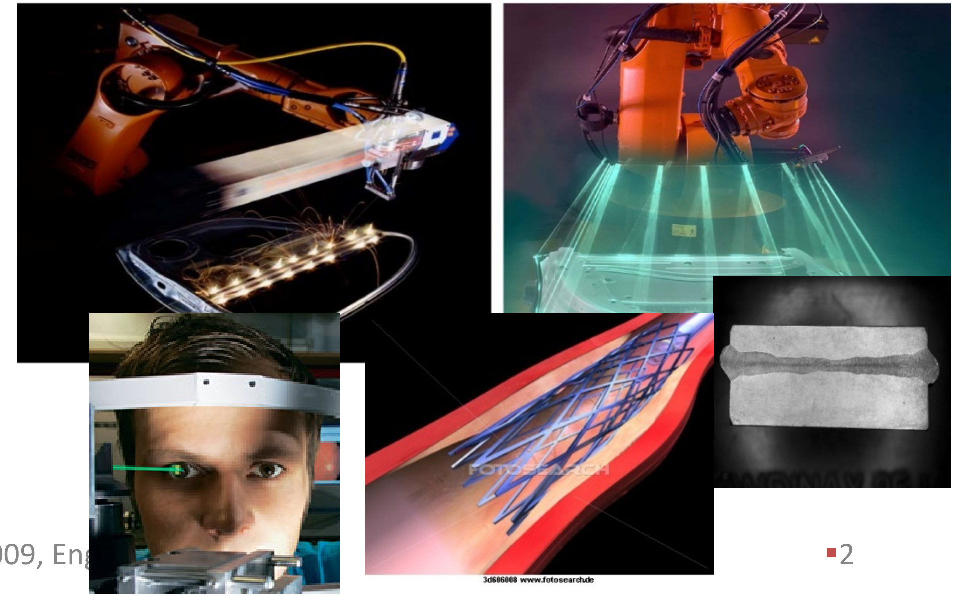
Direct Diode

1. Internet is powered up by pump diode lasers.
   - All long distance links have Erbium Doped Fiber Amplifier (EDFAs)
   - Pump diode lasers to energize the EDFA
   - Compact, solid state efficiency and reliability



2. Power Photonics
   - Today: Classical lasers
   - Will be replaced by
     - Direct diode
     - Diode pumped fiber lasers
   - Compact, solid state efficiency and reliability

Acknowledgement

Acknowledegement

Dr. Dominik Jaeggi, Bookham , Dr. Toby Strite, JDSU, Dr. Alex Ovtchinnikov, IPG, Dr. Berthold Schmidt, Intense, Dr. Michael Lebby, OIDA

Literature

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.*

Swisslaser.net download Photonics 2008 Shortcourse

Telecom Pump Diode Lasers

EDFA: Demonstrated 20 years ago

LOW-NOISE ERBIUM-DOPED FIBRE AMPLIFIER OPERATING AT 1·54 μm

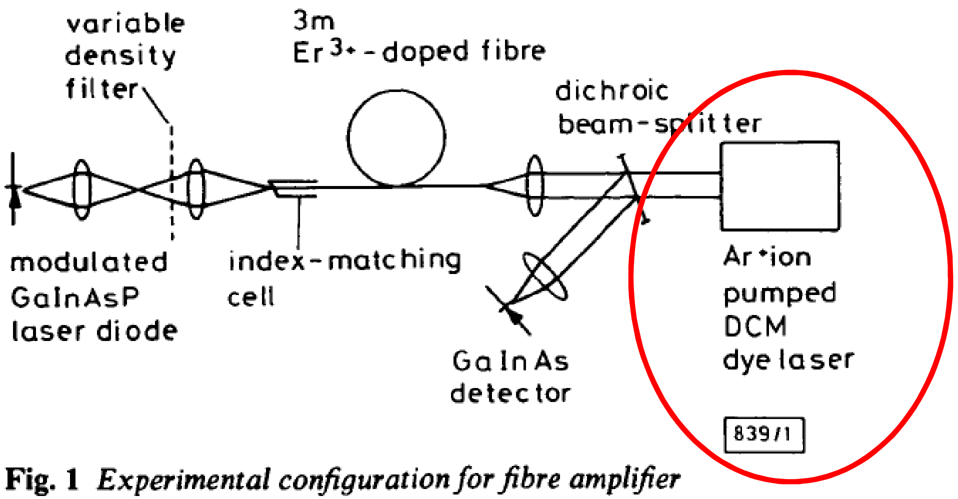


Fig. 1 *Experimental configuration for fibre amplifier*

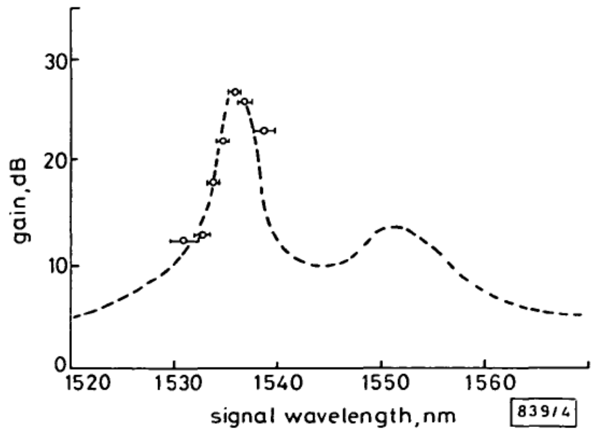


Fig. 4 *Gain spectrum and spontaneous emission*

Points represent experimental measurements and error bars indicate spectral width of diode laser spectrum
Curve represents fluoresence curve

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L. REEKIE
I. M. JAUNCEY
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Department of Electronics
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3rd August 1987

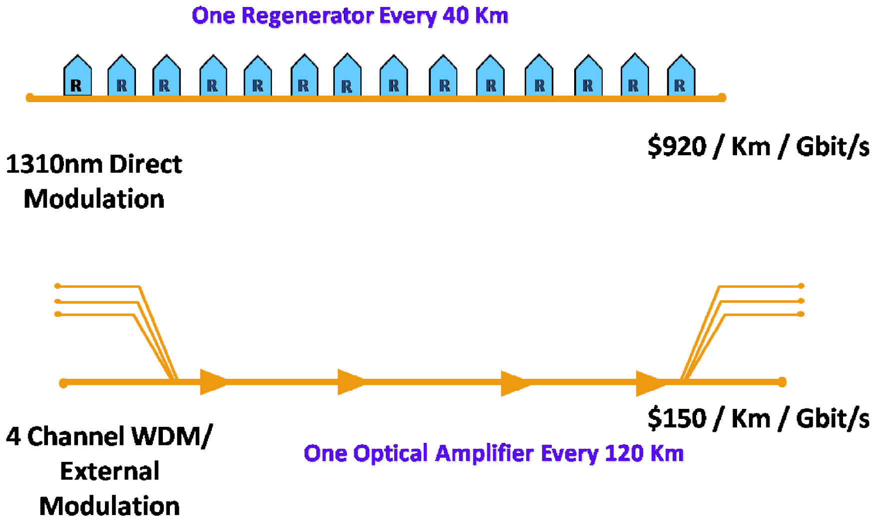
- *All optical silica fibre amplifier at wavelength window of lowest loss. Low noise*

- ***Dye laser pump source***
- ***Prof. Payne had prior to this publication alluded to EDFA in Elect. Lett. in 1985***

ELECTRONICS LETTERS 10th September 1987 Vol. 23 No. 19

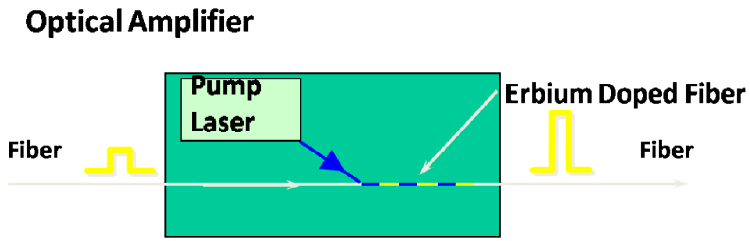
IBM Research Laboratory: 980 Diode Laser

Disruptive Technology:



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

Magic Fiber: Erbium doped fiber



Optical Amplifier:

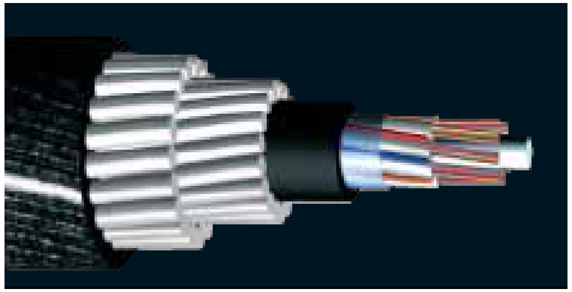
- 980nm pump laser as power supply
- We were the only laser supplier for high power and high reliability

Example: Intercontinental

- TAT-8 (1988): 0.28Gb/s per fiber
  - 46k$/channel
- TGN (2004): 1000Gb/s per fiber
  - 12$/channel

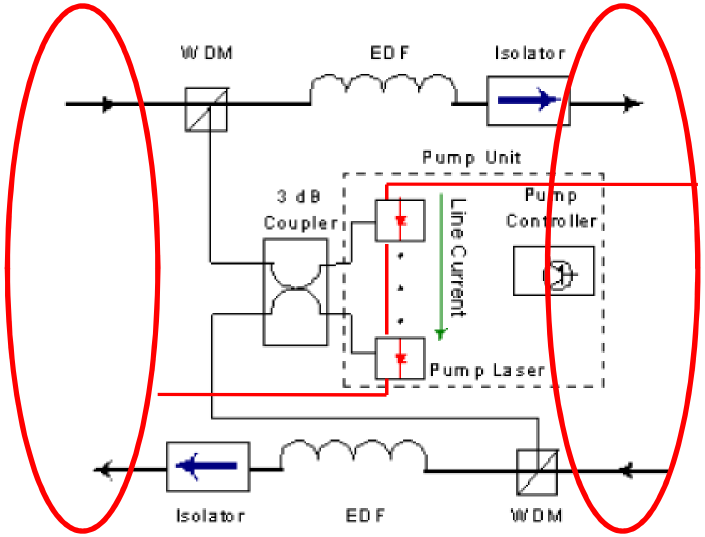
EDFA Repeatered Transmission

1. Intercontinetal Lines
   - Typically submerged cables 64*10Gb/s over 6000km
   - EDFA every 50km
   - 10.. 70 fiber pairs per cable



2. Long distance links
   - Landlines

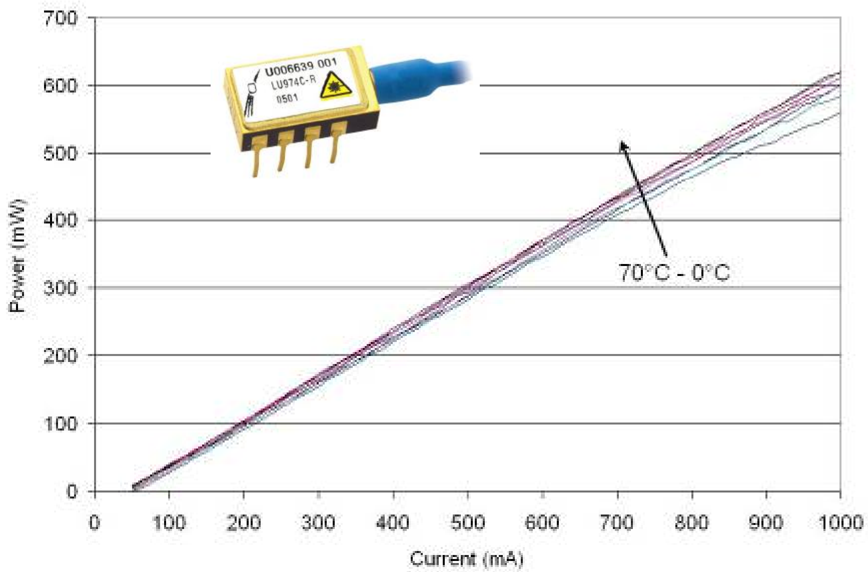
3. TV Distribution
   - Power amplifier before splitting lines to brodcast TV signal through many fibers

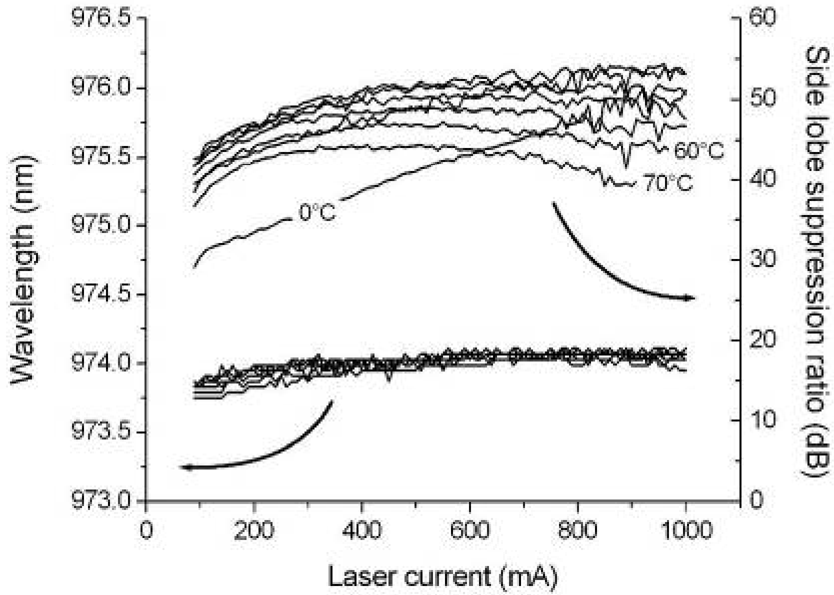


Alltogether: A few million pump lasers powering up these links

Narrow Stripe
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





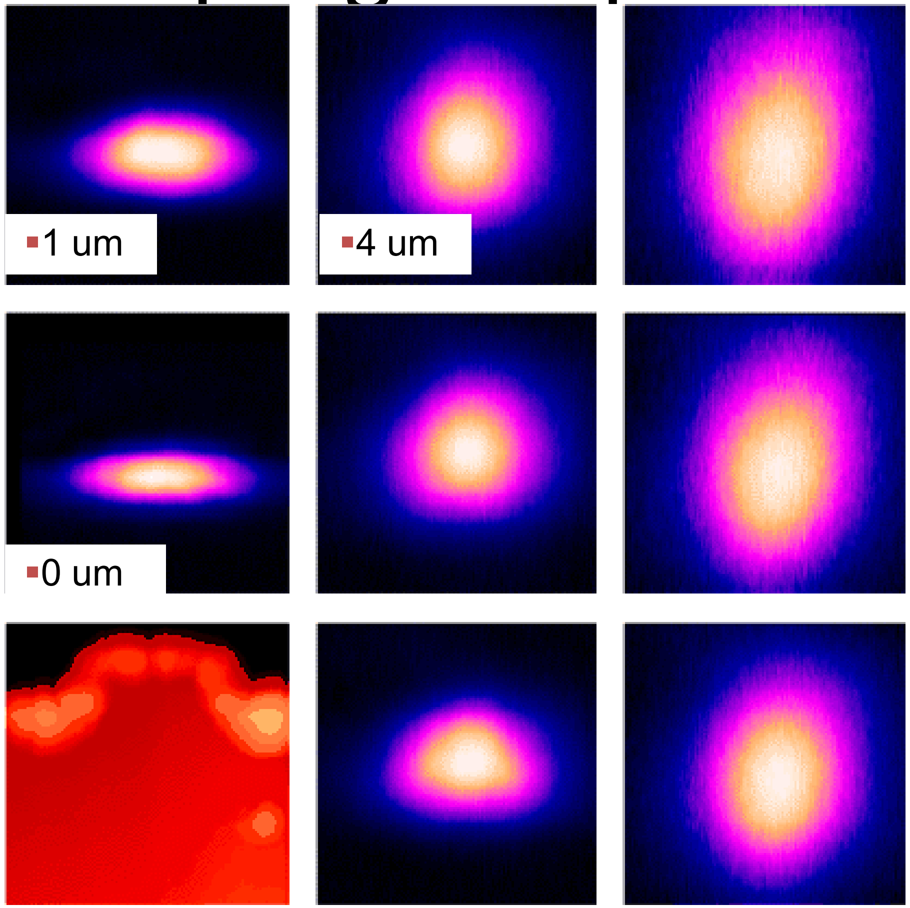
Different Pump Wavelength for Communication

Figure of Merit	980nm SM EDFA	940nm MM YEDFA	1480nm SM EDFA	14xxnm Raman	Comments
Noise	Very good	Good	OK	Excellent	
Max Output Power	Good	Excellent	Good	na	
Wallplug conversion efficiency	5%..15% (uncooled)	10%..15%	2%	1%	Output/Input Power
Gain flatness	Good	Poor	Good	OK	
Bandwidth	Wide (C+L)	Poor	Wide (C+L)	Excellent	
Reliability	Excellent	OK	Excellent	Excellent	
Max temperature	T<75C	T<45C	T<70C	T<70C	
Packaging	Simple	Simple	Lens Isolator	Simple	Cost
System embedding	Easy	Easy	Easy	Difficult	
Application	Generic	CATV Booster	Use only as remote preamp	Use for expansion beyond C and L band	

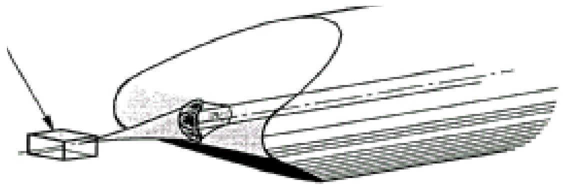
1. 9xx
   - Dominant technology for internet, CATV
2. 1480 and 14xx
   - Today for niche applications (remote EDFA and Raman)

Cost: Dominated by coupling pump diode beam to fiber

Narrow Stripe
Coupling Pump Diode Beam to Fiber



Prof. Unlü, Boston



Single Mode Fiber: NA=0.12

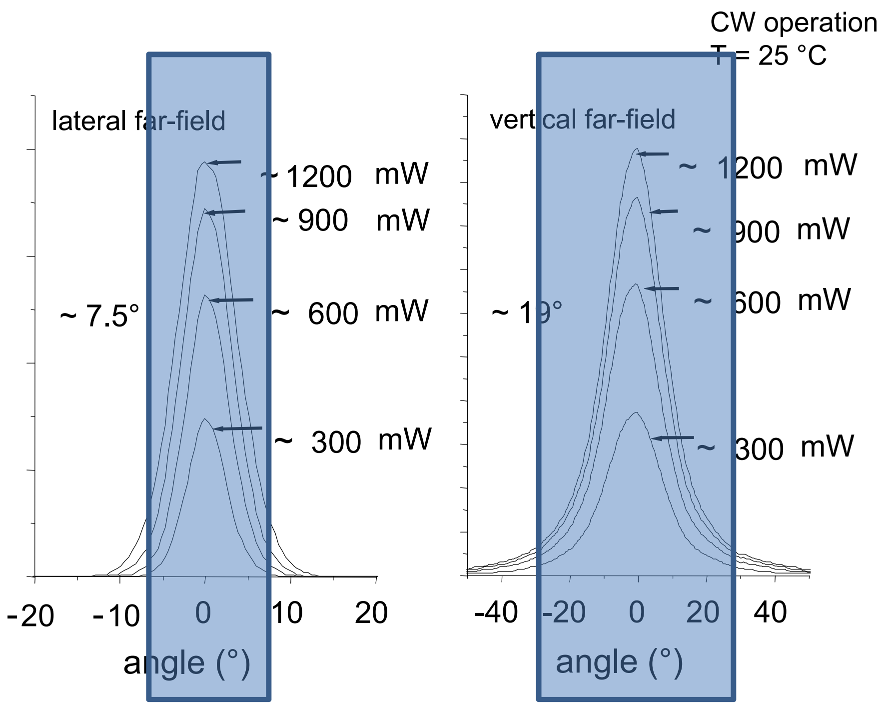
Laser Diode:

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

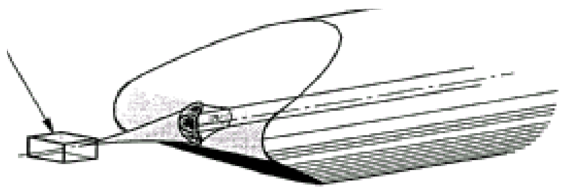
Coupling

- At distance of 4um: Profiles match

Narrow Stripe
Coupling Pump Diode Beam to Fiber



- NA=0.12
- NA=0.5



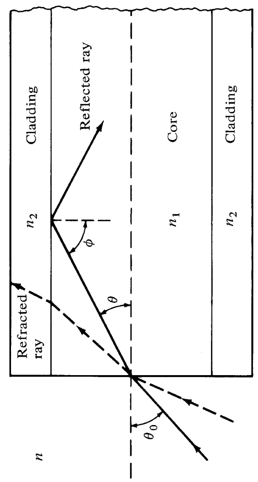
Single Mode Fiber: NA=0.12

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 to match to NA=0.12 of the fiber

- NA=sin(angle)~angle
- Slow axis: NA=0.12 ~7deg
- Fast axis: NA=0.5~30deg

Narrow Stripe
NA design of waveguide

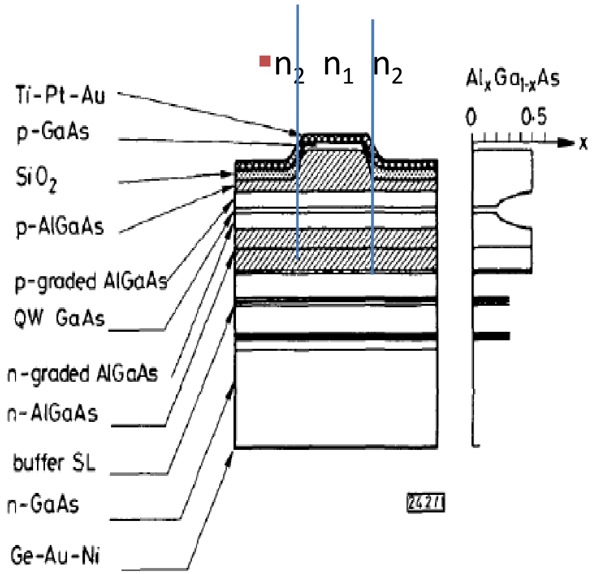


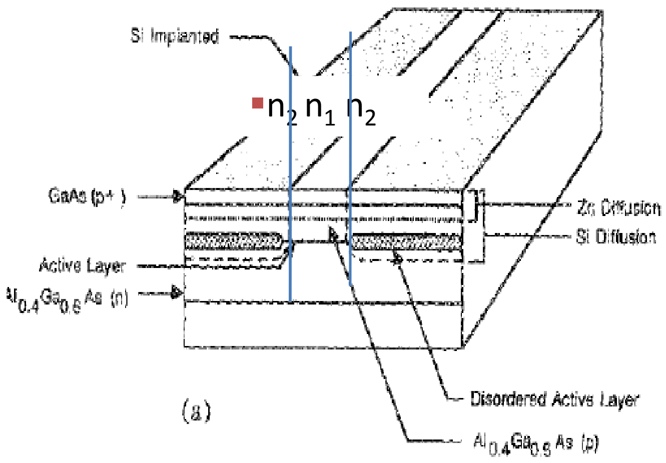
Pump Diode is dielectric waveguide with index n1, n2 and NA

$NA=(n_1^2-n_2^2)$~SQRT(2*dn*n) dn= n_1-n_2

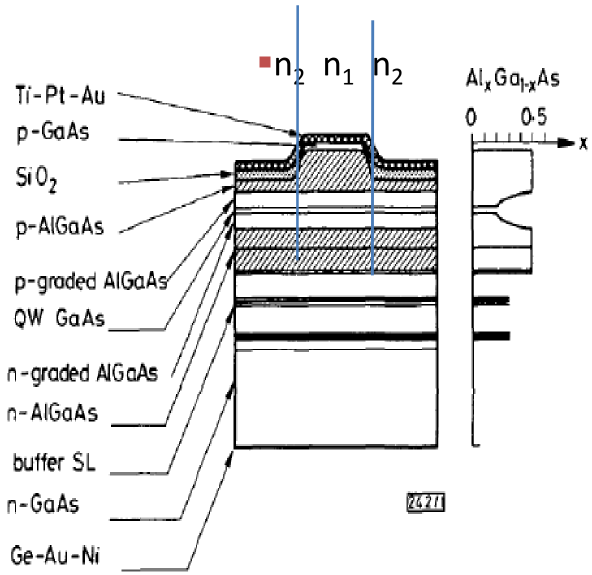
dn=1/2*$(NA/n)^2$ **->dn=5*10^{-4}** **(**NA=0.12 and n=3.6)

Need a week waveguide: Ridge or disordered

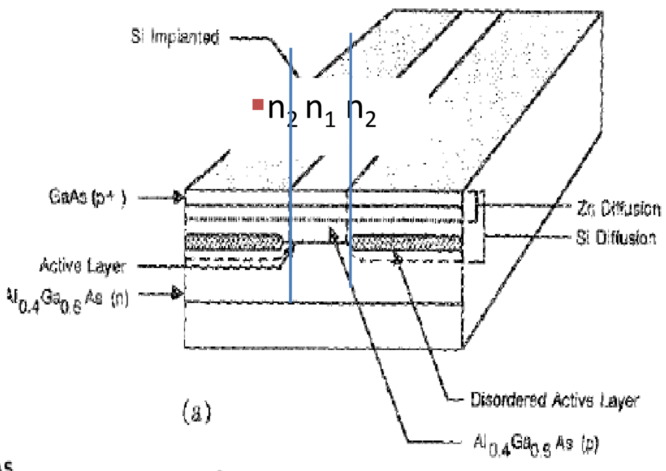


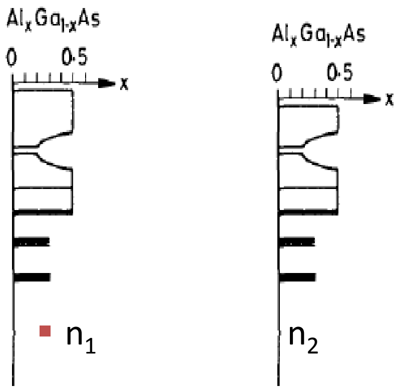


Pump Diode Beam: Slow axis
Effective Index approach



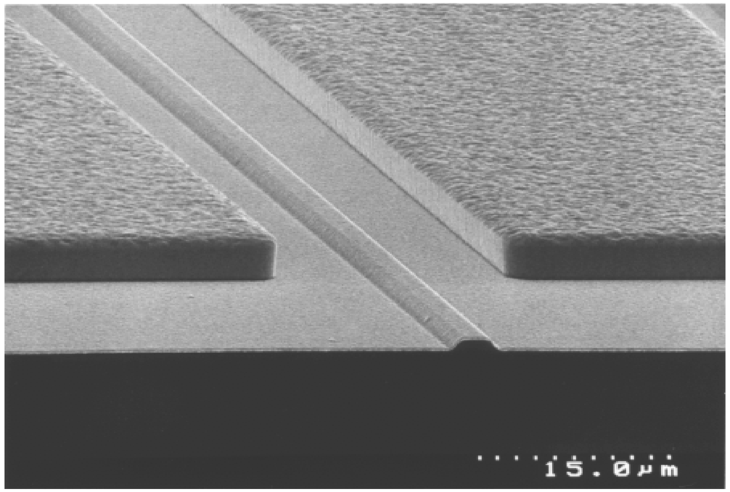
$dn=n_1-n_2$

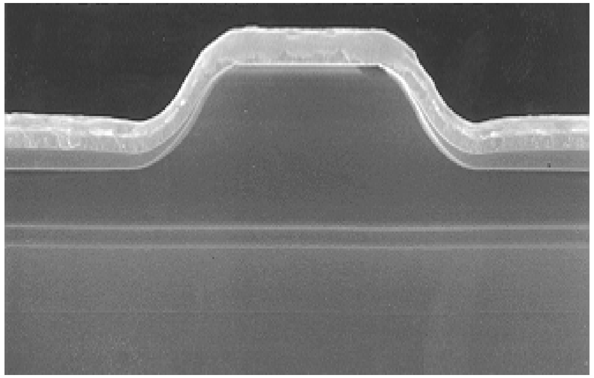


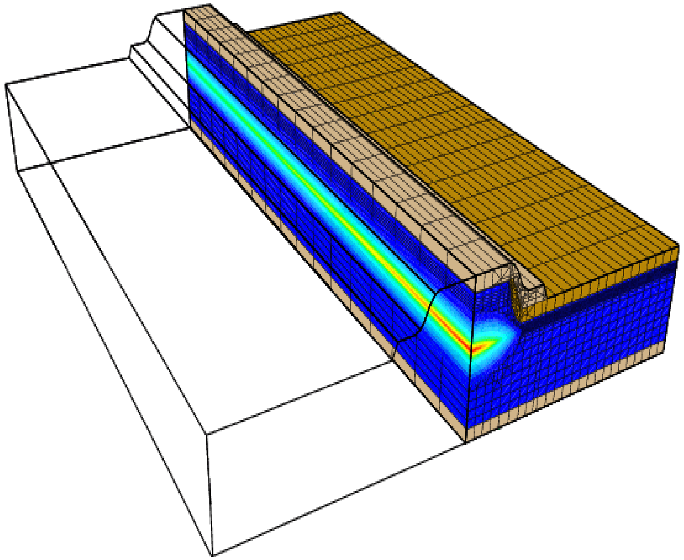


- Effective Index approach
  - Calculate effective index of planar waveguides (center and outside)

Narrow Stripe
Ridge waveguide

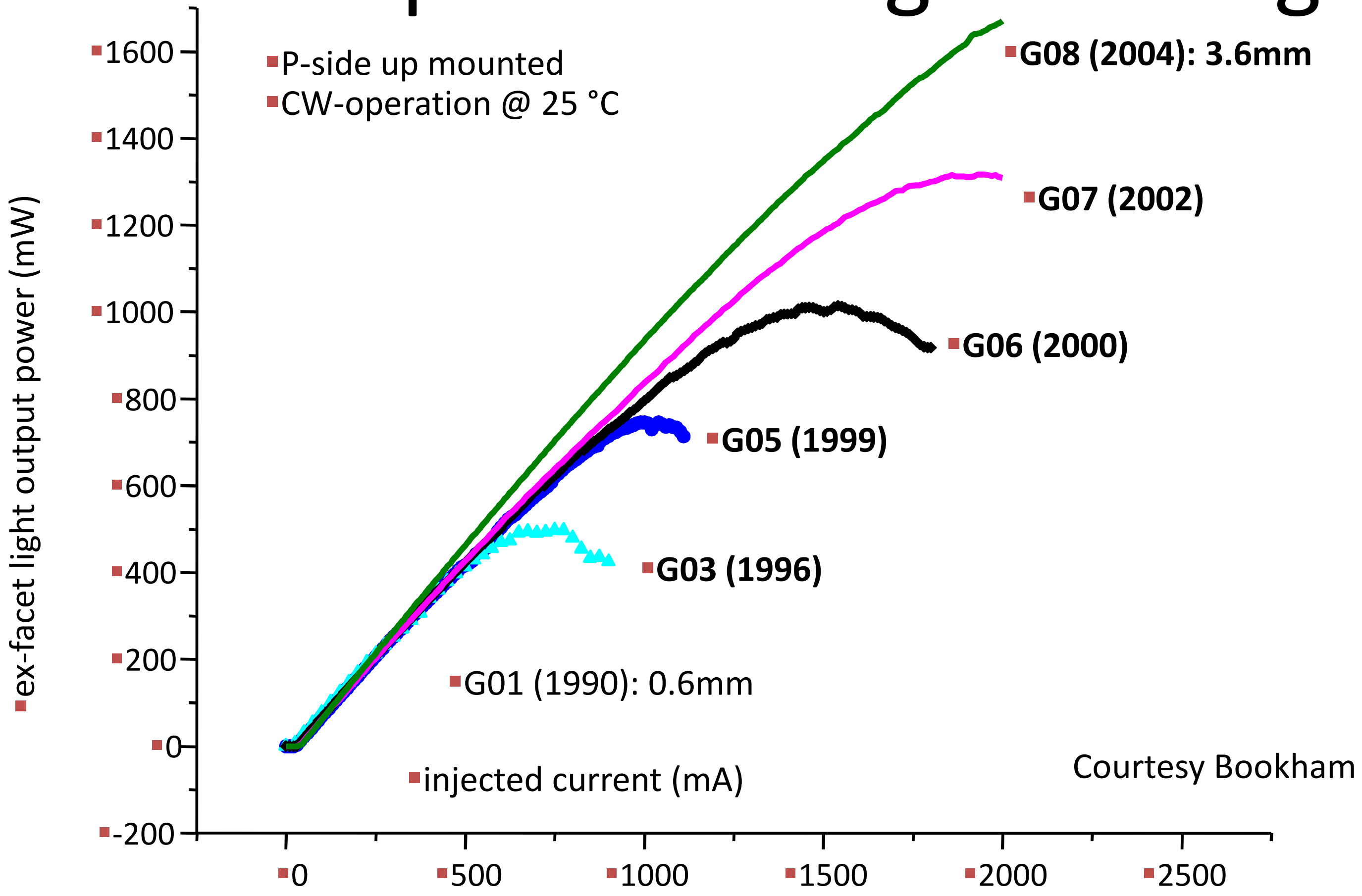






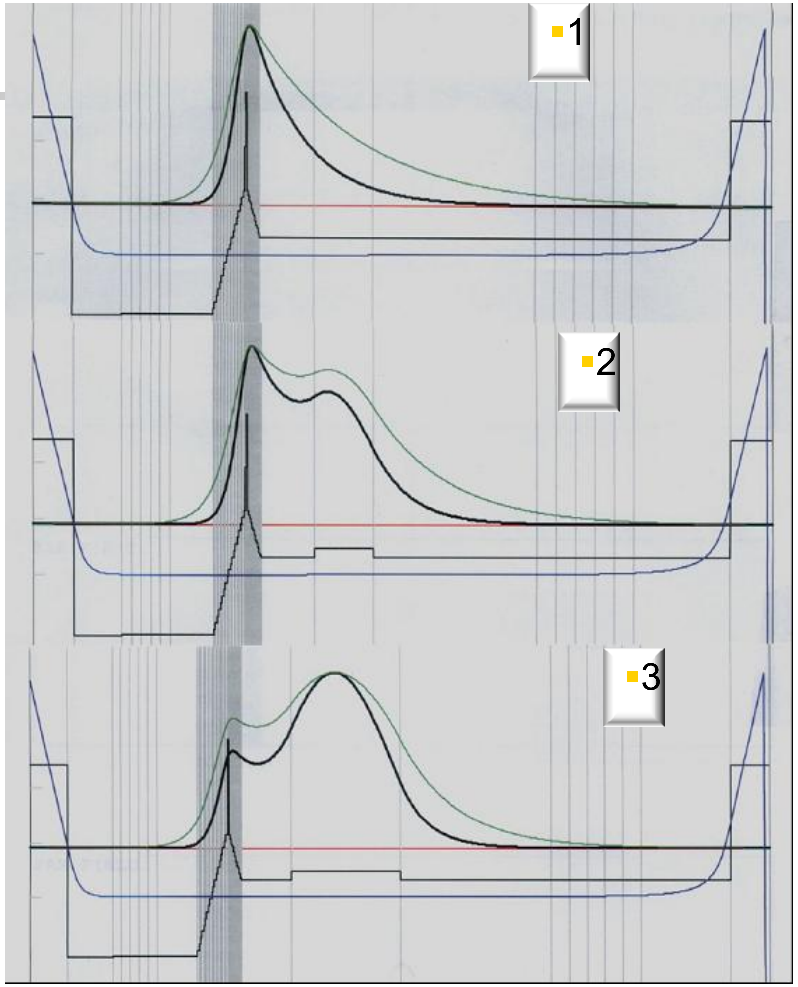
- Ridge Waveguide
  - One growth step, simple process
    - Built in reliability
    - InGaAlAs for best material properties
  - Confinement
    - Index guided mode: High linear power and excellent coupling to fiber
    - Temperature insensitive current confinement
  - Scalability
    - Increase power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

Narrow Stripe
980nm Pump Diode Length Scaling



Improve performance by length scaling

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

Narrow Stripe
Length Scaling (Dilute waveguides)

Increase power: Make laser longer to better remove the heat.

- Most important laser parameters:
  - Gain(G), efficincy(η), photon lifetime (τph), internal power ratio (Pr)

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

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

  - absorption(α), lenght(L), confinement (Γ), front mirror reflectivity R (backmirrror reflectivity=1)

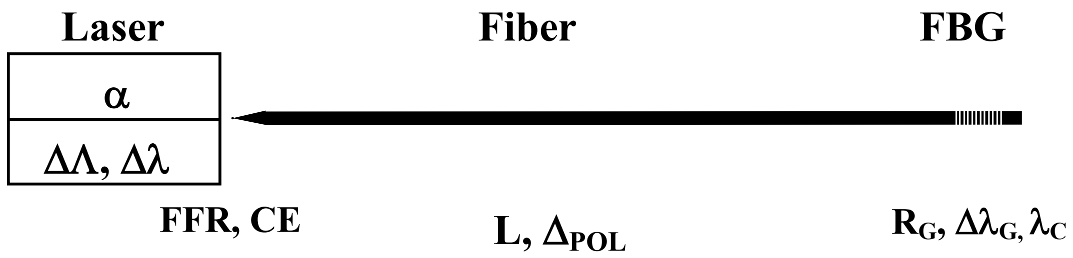
- Keep Gain(G), efficincy(η), and internal power ratio (Pr) constant
  - > Scaling rule for R, Γ and α for lasers with length L

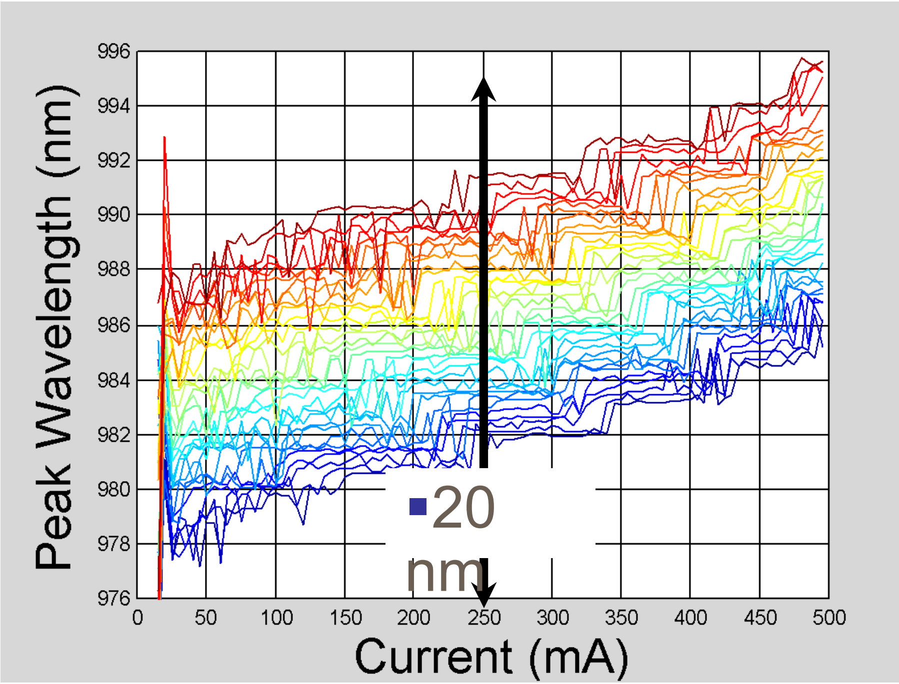
$$R(L) = R(L_0) \qquad \Gamma(L) = \frac{L_0}{L} * \Gamma(L_0), \quad \alpha(L) = \frac{L_0}{L} * \alpha(L_0)$$

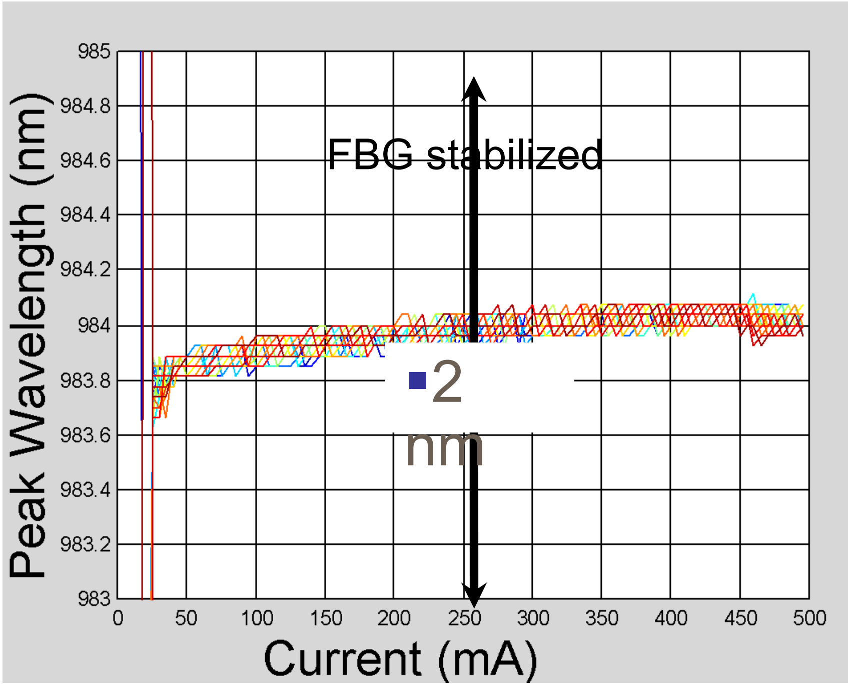
- **Output power scales then linearily with length L (at const current density)**
  - For η=85%, Pr=3, G=550cm-1 (independent on length)
  - **2mm long chip: R=0.03, α =1.6cm $^{-1}$ and Γ=2%**
  - **4mm long chip: R=0.03, α =0.8cm $^{-1}$ and Γ=1%**
  - **8mm long chip: R=0.03, α =0.4cm $^{-1}$ and Γ=0.5%**

  - **> Need low loss and low confinement structures**

Wavelength stability

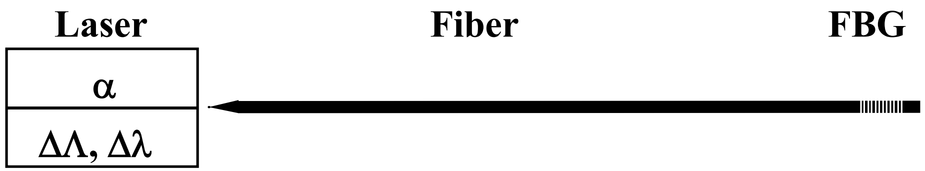


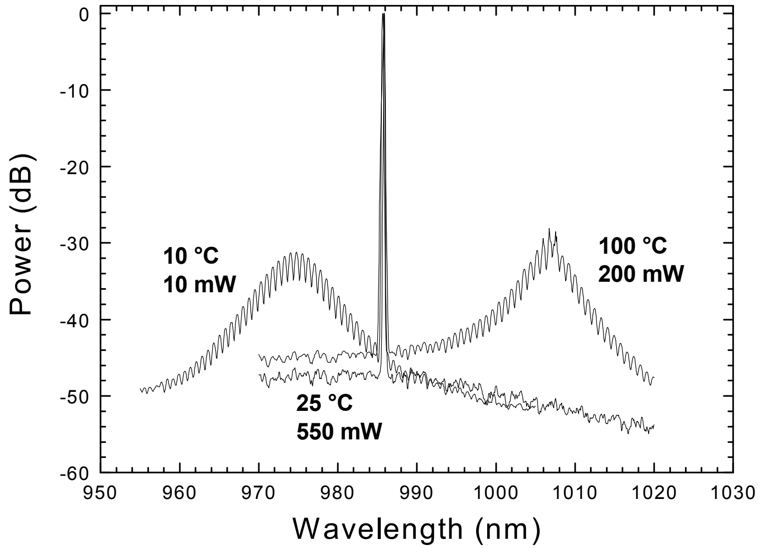




17nm Free Running Wavelength Shift
for 25mA - 500mA & 10°C - 40°C
=> 0.33nm/°C and 0.015nm/mA

Wavelength Stability with FBG

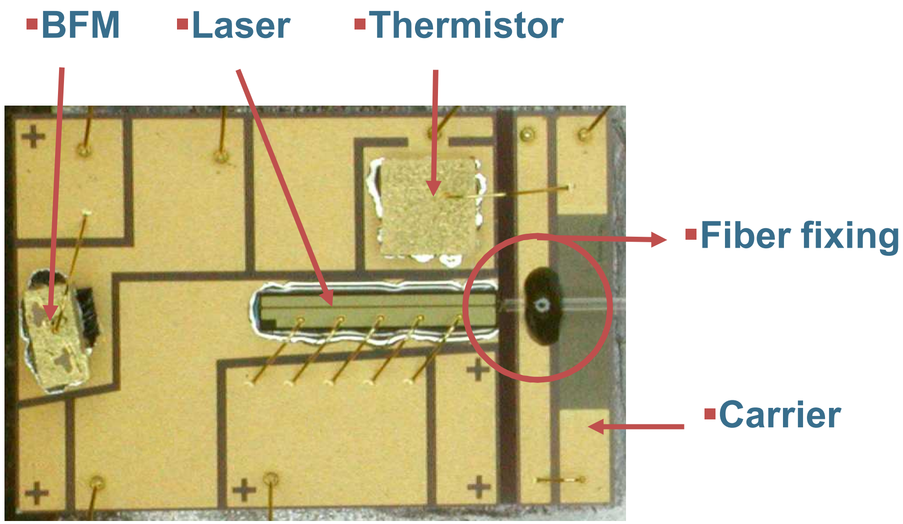


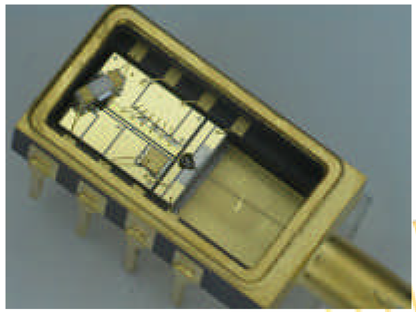


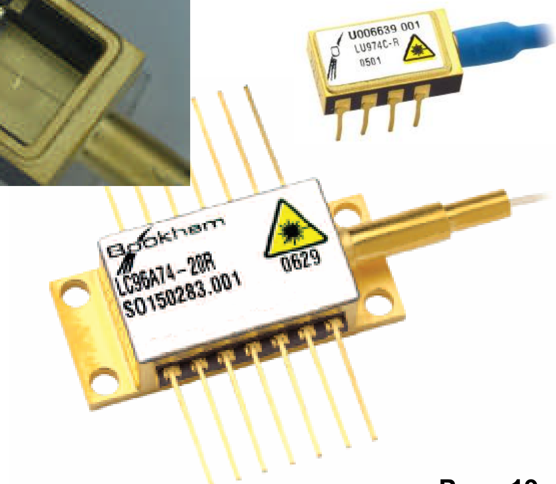
- External fiber Bragg grating to lock wavelength

Single Mode Fiber Pump Module

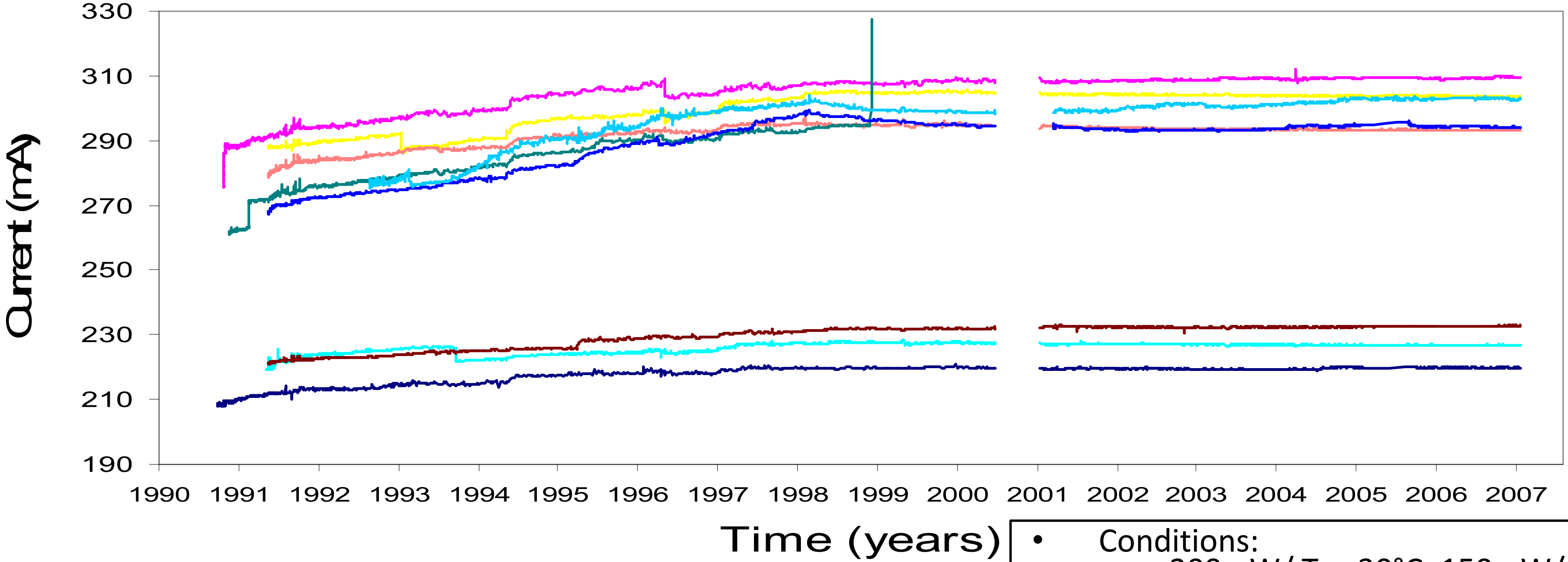
- Fully monolithic planar AlN substrate
  - Extremely low mechanical creep
  - Cost effective automation
  - Excellent thermal properties
- Used in Butterfly packages and coolerless MiniDIL
  - i.e. 400 mW Submarine MiniDIL, 600mW Butterfly







Narrow Stripe
Reliability track record

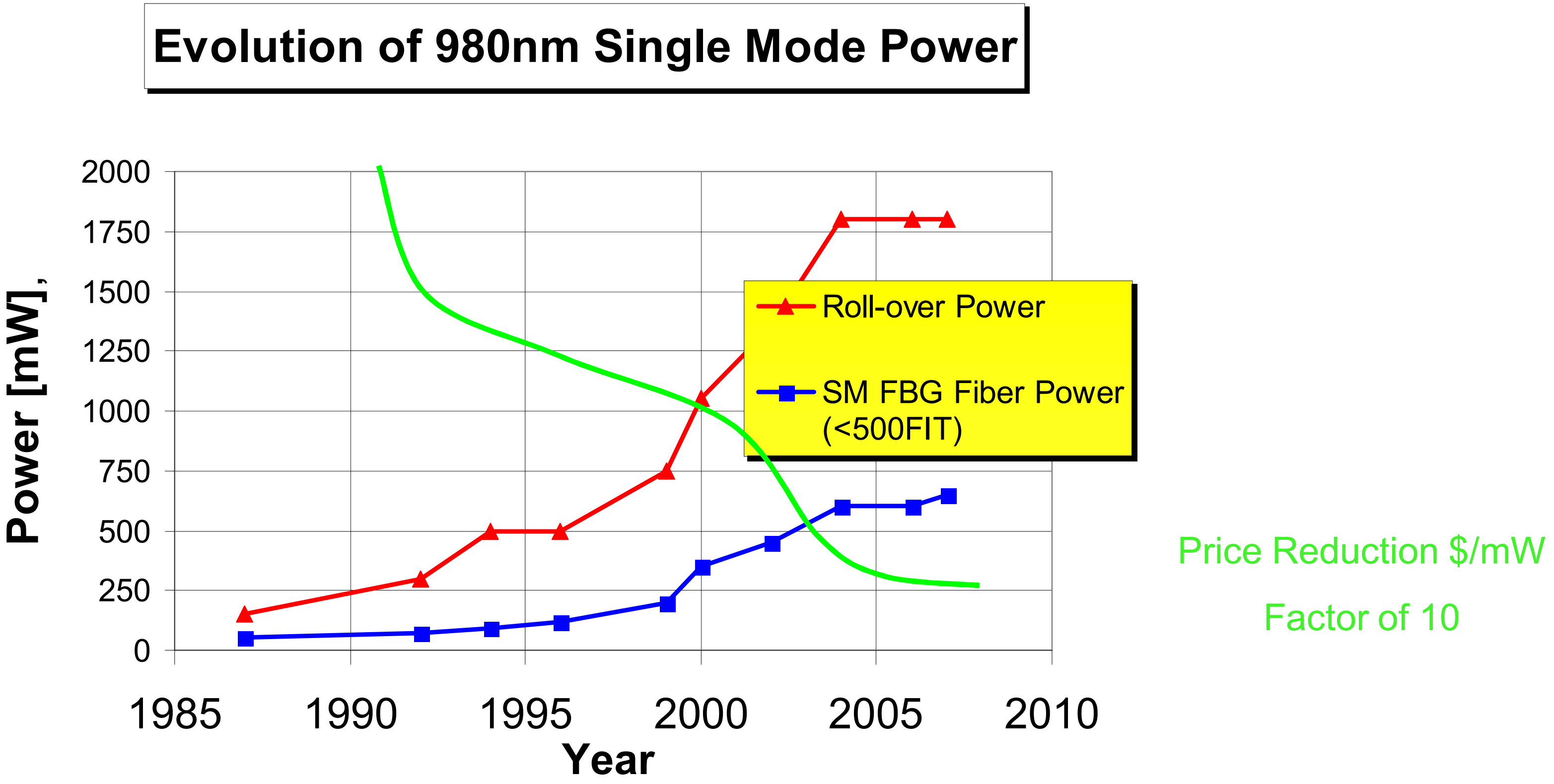


- Conditions:
  - 200mW/ T_{hs}=30°C; 150mW/ T_{hs}=75°C
- Reliability at 130mW/ 25°C:
  - Sudden Fail: 32 FIT
  - No wear-out

Bookham Track Record

- First field deployment of 980nm pumps
  - 1993 (MCI from Chicago to Sacramento)
- Shipped from Zurich more than 1’000’000 devices into terrestrial deployments
  - Field reliability: <50FIT (0.05% return/year)
- 50’000 pumps in underwater transcontinental links
  - no fail of consequence
- Widespread
  - More than 50% of all optically amplified telecom and internet links worldwide are based on this technology (from Zurich directly or through licensed partners)
  - Courtesey Bookham

Narrow Stripe
980nm Single Mode Pump Diode:



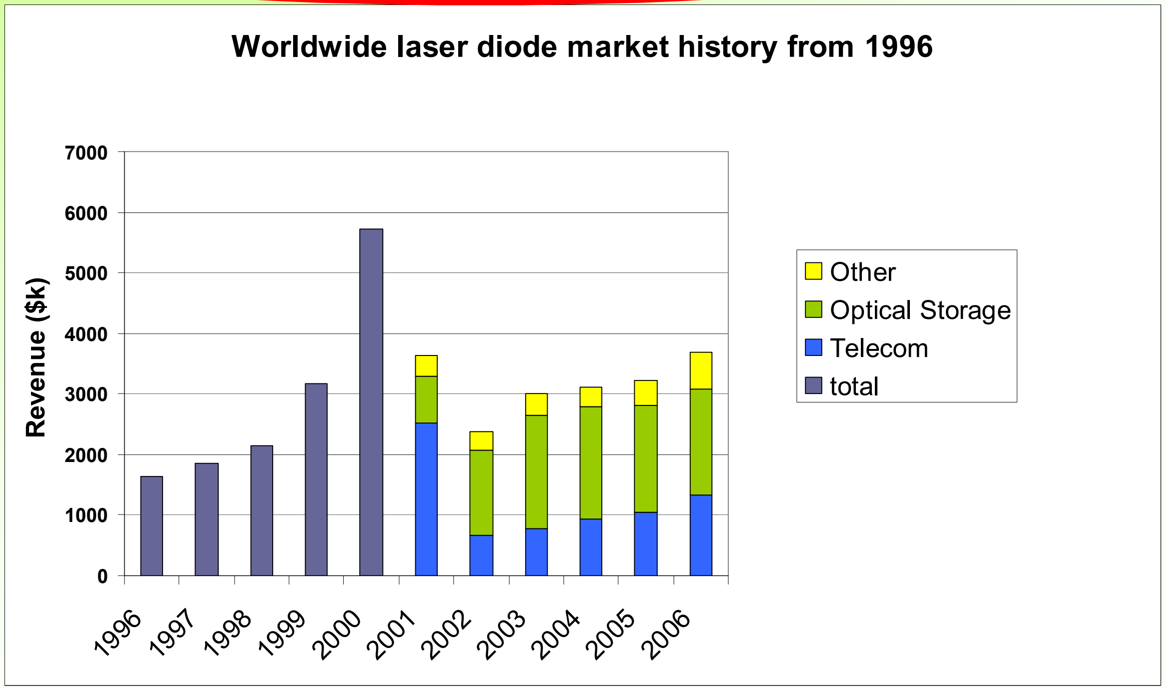
980nm Pump Diode Lasers: Matured

-> Power has reached plateau at 700mW in Fiber

-> Cost to develop next length structure (lower waveguide loss and confinement) is to expensive for telecom market

Diode lasers will struggle to grow revenue

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

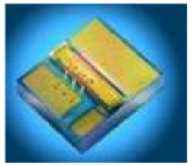


▪ *Sources: OIDA, OIDA members, Laser Focus, OIDA consultants*

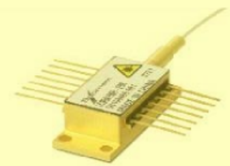
▪Michael Lebby
(lebby@oida.org)

▪Telecom and storage entering maturity?

SM Narrow Stripe Single Emitters





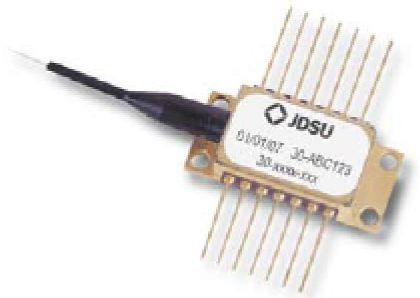


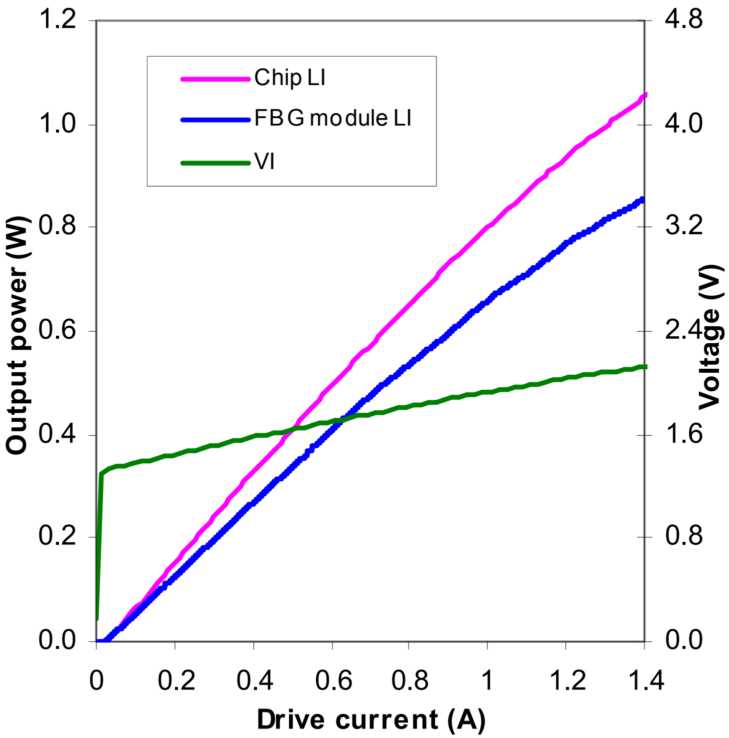
Chip Gen	980 Chip on Submount	980 Uncooled MiniDIL	980 Cooled BTF Package	976 SHG Pump BTF Package	10xx Laser BTF Package
G06	450mW		300mW		
G07	600mW	200mW	400mW	300mW	
G08	900mW		750mW		1 .5-2A pulsed

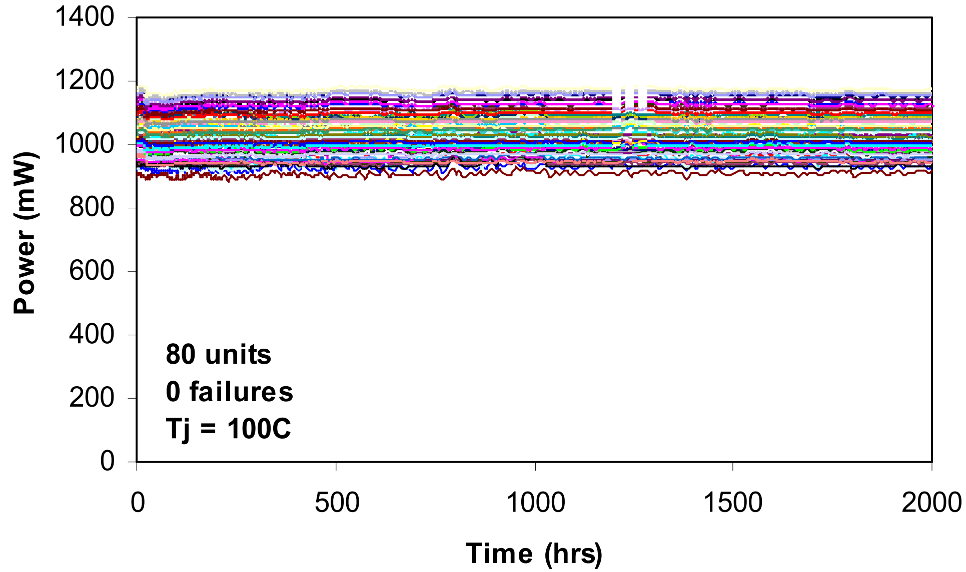
- All wavelength stabilized
- <100FIT

- Signal Lasers

JDSU 980nm Single Spatial Mode Pump

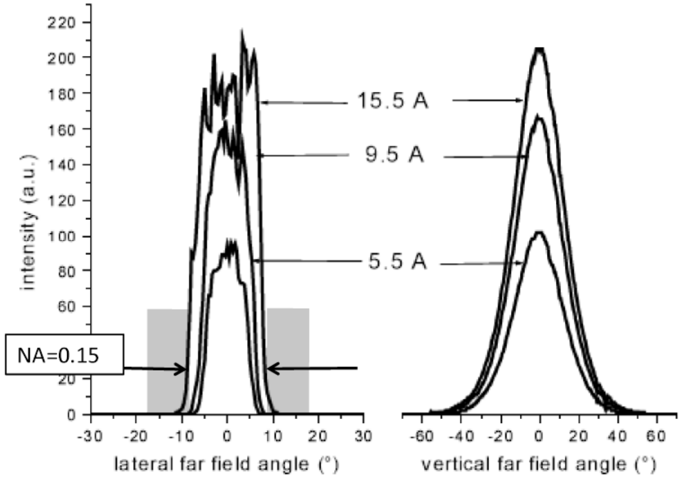


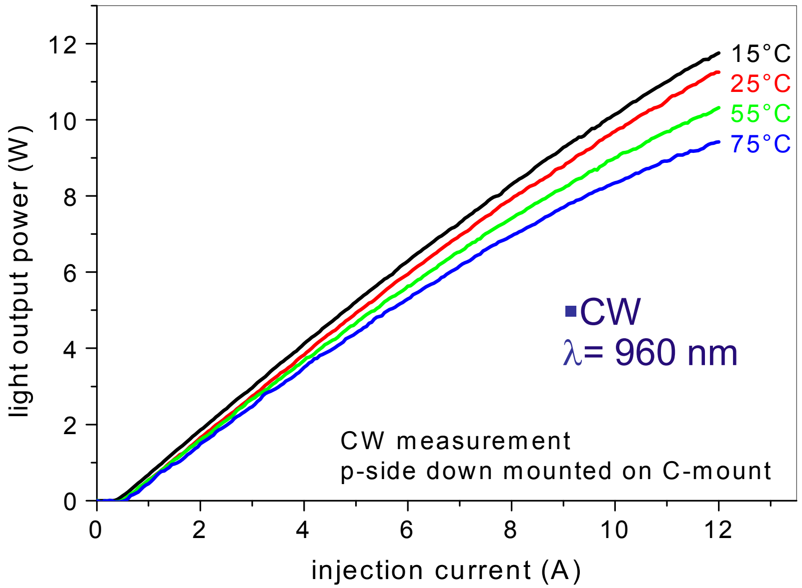


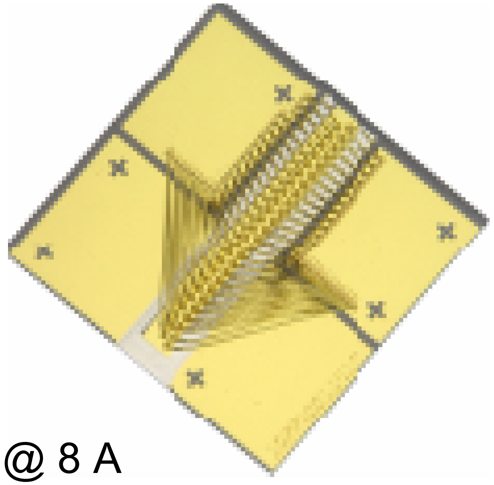


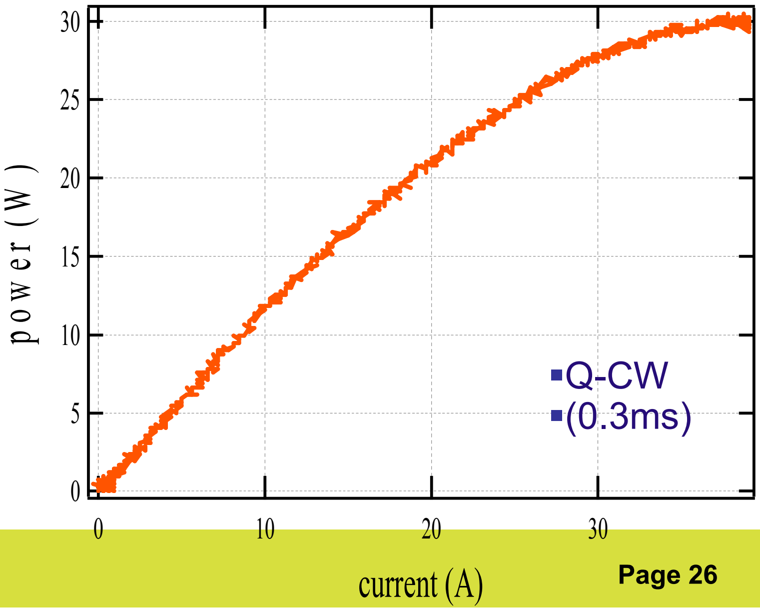
- New FBG-stabilized pump module
  - 660mW kink-free power
  - 45 FIT chip reliability at 830mW
- Mature package platform
  - 5 billion field hours
  - 5 FIT field reliability

SES8-9xx-01 performance



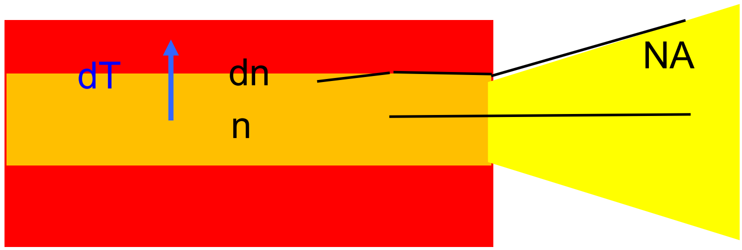




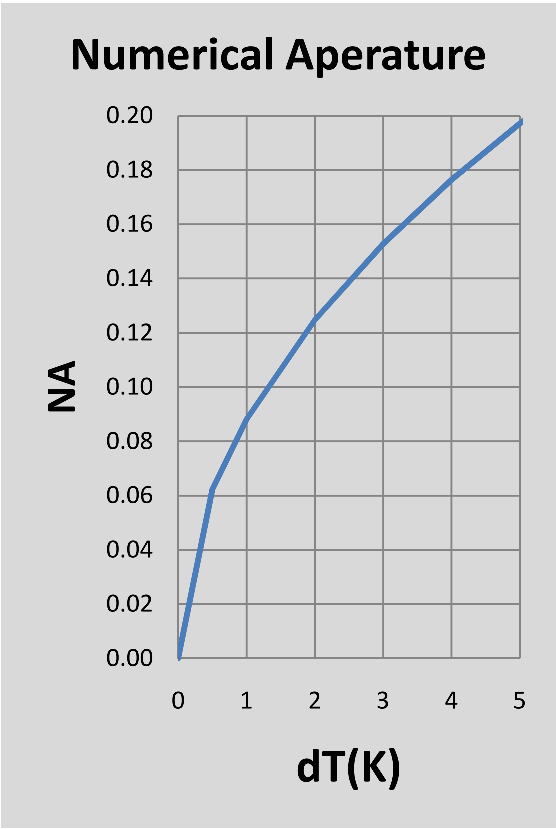


- Electro-Optical
  - Power: 8 W @ 8 A
  - Reliability: <5% fail in 10‘000h

Broad Area Pump Diodes
Thermal Blooming at high Power



$$\mathrm{NA} = n \sin \theta_{0,\max} = (n_1^2 - n_2^2)^{1/2} \approx (2*n*dn)^{0.5}$$



dn=dn/dT *dT

NA=0.1 > dT<1.5K !!

dn/dT=3*10^{-4}, n=3.6

Avoid temperature rise in active stripe

> High power conversion efficiency

> Long cavities

> Good heatsinking

Broad Area Pump Diodes History to reduce NA

Designidea: Reduce thermally broadended NA by

1. Coherent arrays
2. Surface grating lasers
3. MOPA
4. Taper Laser
5. Alpha DFB
6. Large Area VCSEL

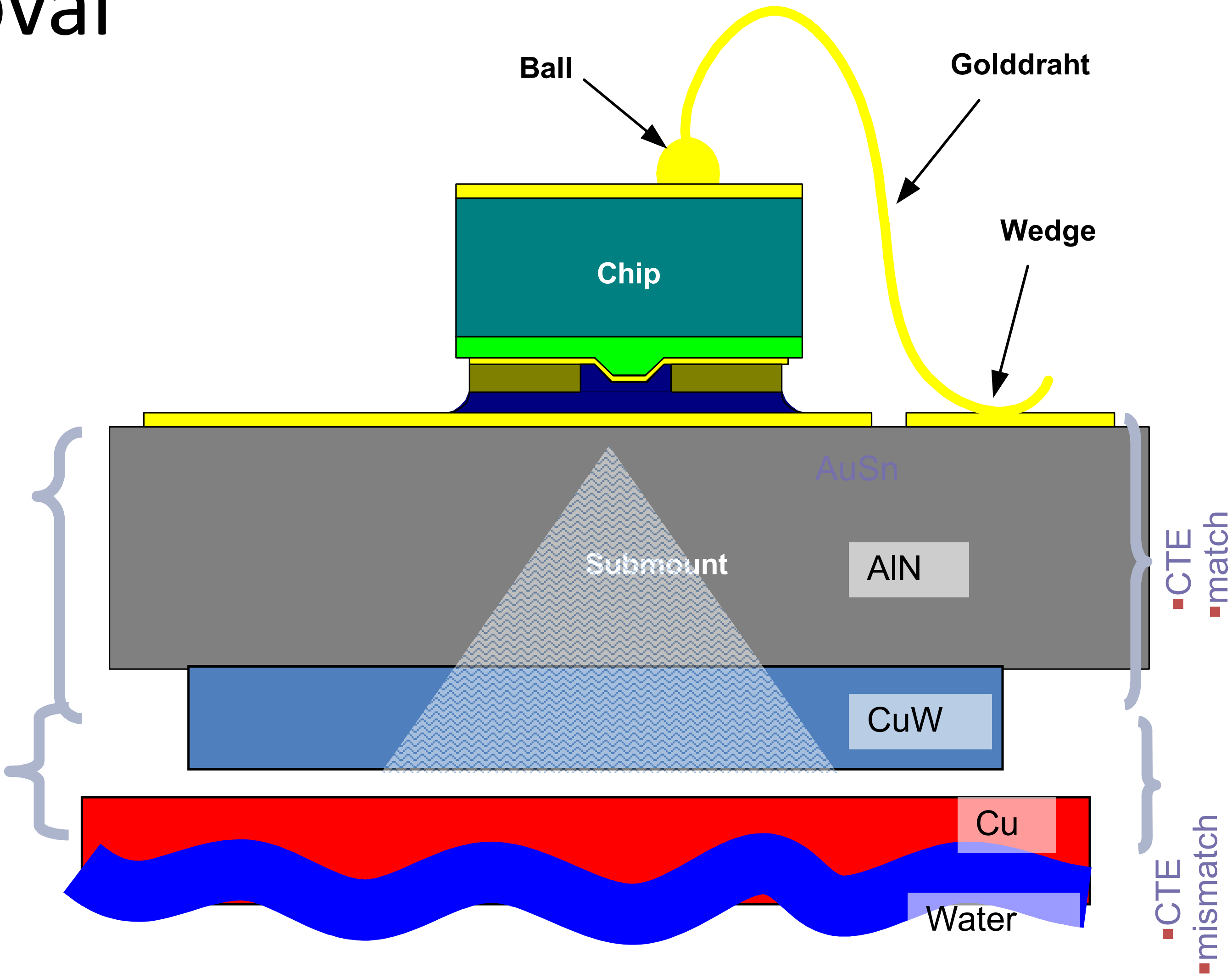
None of these designs was successful.
Too difficult to manufacture
Reliability (beam stability) issues

Today, simple single stripe broad area are mostly used with good thermal control

9xxnm Multimode Pump Diodes
Heat removal

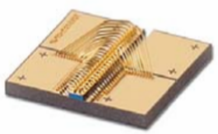
- Soldered to
- expansion matched
- materials for
- heat spreading

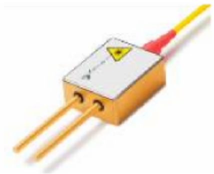
- Mechanical pressure thermal contact to copper heatsink



9xx MM Broad Area Single Emitters

Bookham






WL	Chip on Submount	Chip on C-Mount	Uncooled Module 2-pin	Multi-Emitter Module 2-pin
915, 940, 960, 975nm	**9W** SES9-9xx-01	**9W** SEC9-9xx-01	**8W** BMU8-9xx-01/2-R	**20W** MU20-9xx-01/2-R
915, 940, 960, 975nm	**11W** SES1 1-9xx-01	**11W** SEC1 1-9xx-01	**10W** BMU10A-9xx-01/2-R	

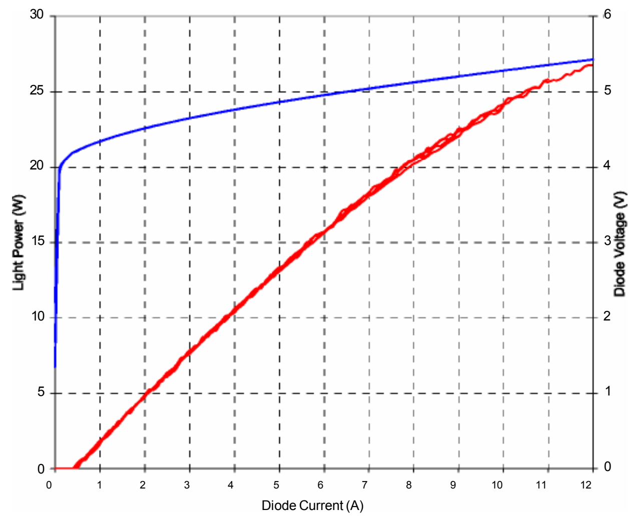
- Chip stripe width: 90um
- AlN submount or Cu C-mount
- Passively cooled packages with floating anode/cathode
- 105um fiberwith 0.22/0.15NA

20W Multi-Emitter Module

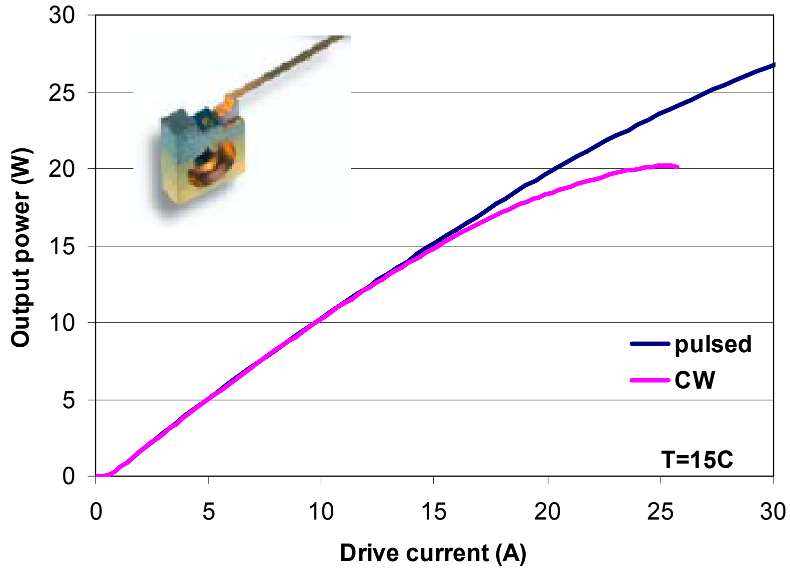
- **Module**
  - – 3 single emitters inside
  - – 2-pin package
  - – 0.15NA or 0.22NA in 105um fiber
  - – Floating anode/cathode
  - – 1060nm blocking filter included

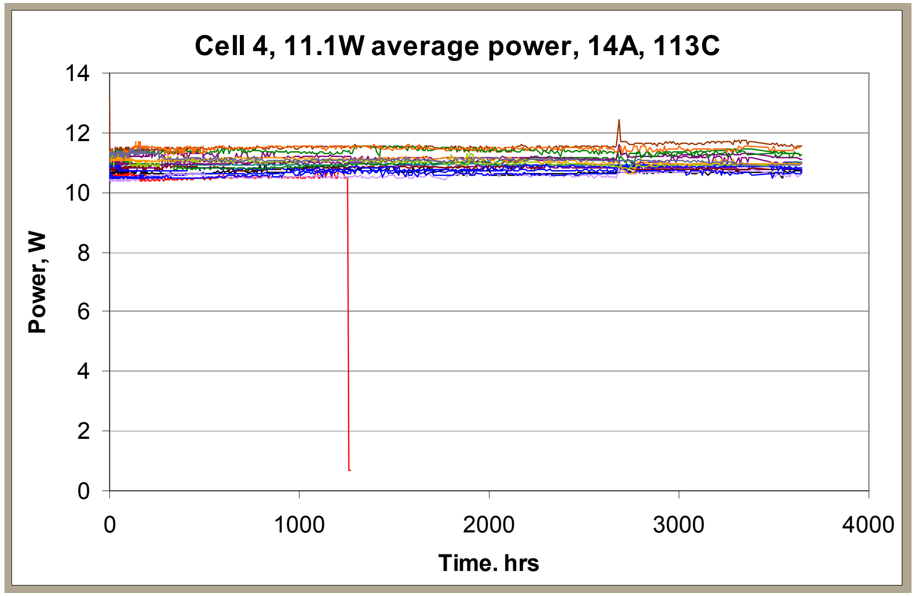
- **Electro-Optical**
  - – Power: 20W
  - – Current: <9A
  - – Wavelengths: 915, 940, 960, 975nm

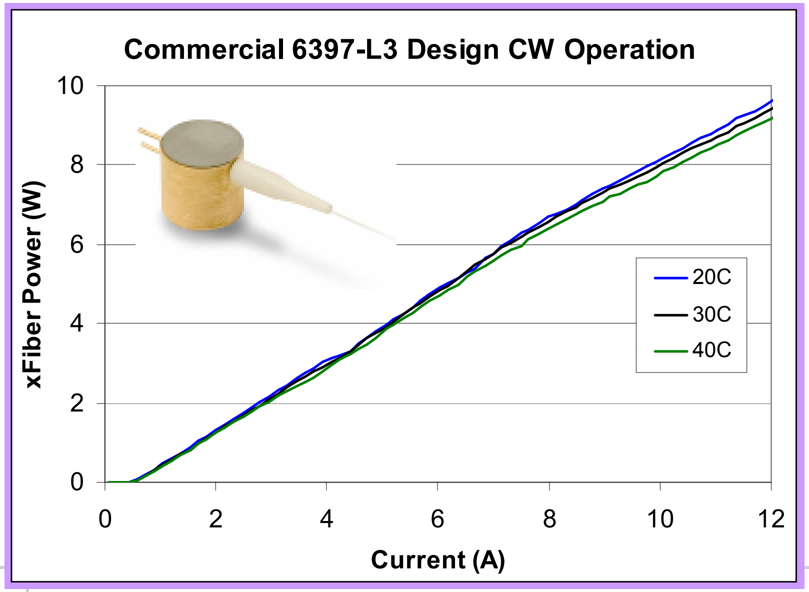
P-I -V Curves of 0.15NA 20W Modules:



JDSU 9XXnm Multi Mode Pump

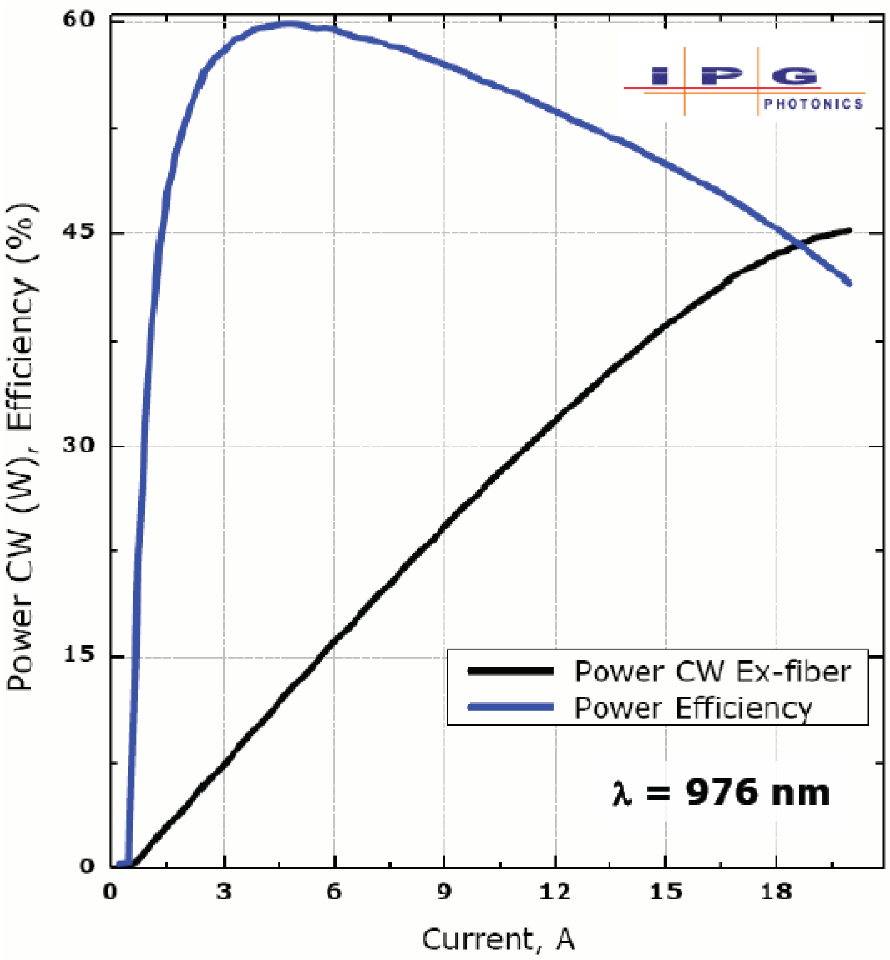






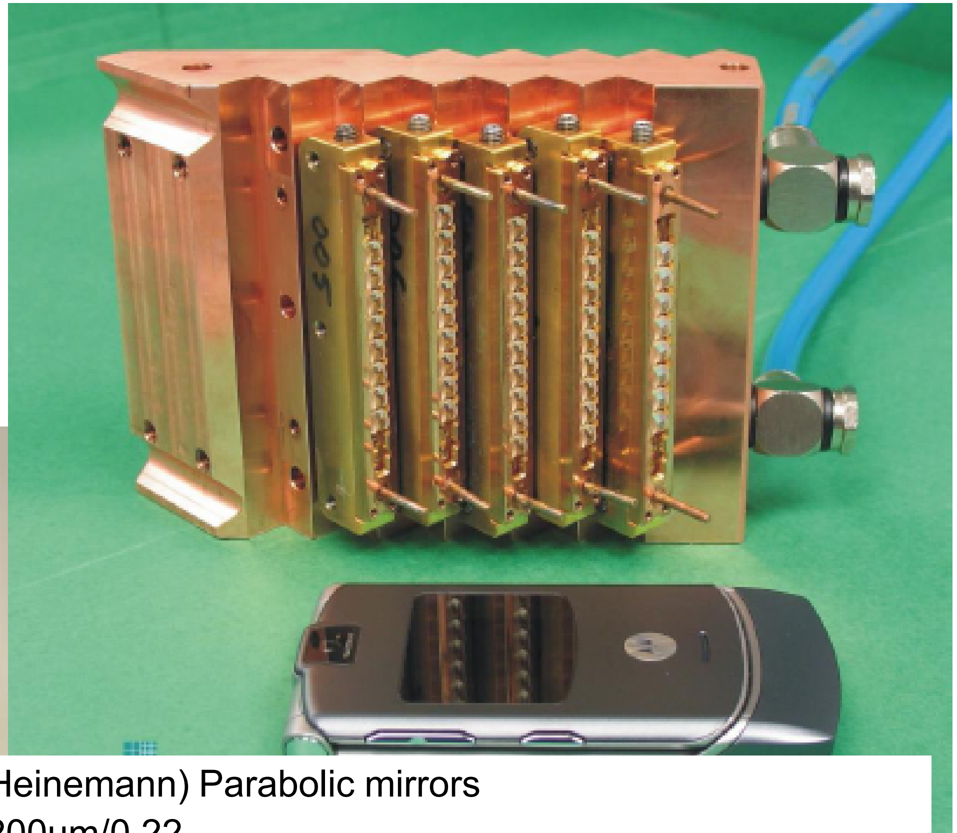
- 100μm wide aperture chip
  - 20W CW rollover power
- 105μm diameter, 0.2NA fiber
  - 8W rated power at 10A

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 (Heinemann) Parabolic mirrors
  - 500W 200um/0.22
  - Alignment (lens<50nm, PA FA/SA 0.1mrad, lens 0.05mrad).

Fraunhofer USA Center for Laser Technology

visotek inc. smart laser tools

Power Photonics
Fused and Proximity Combiner

Fused: (6+1)*1

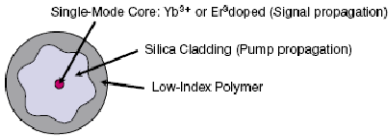


Figure 2 Cross-section of double-clad optical fiber for cladding pumping.

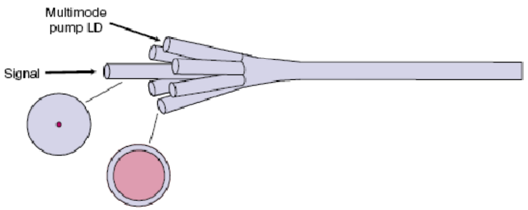
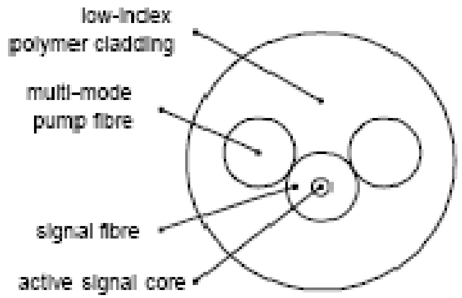
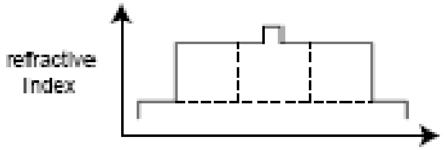


Figure 3 Schematic of tapered fiber bundle.

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

Proximity: (2+1)*1

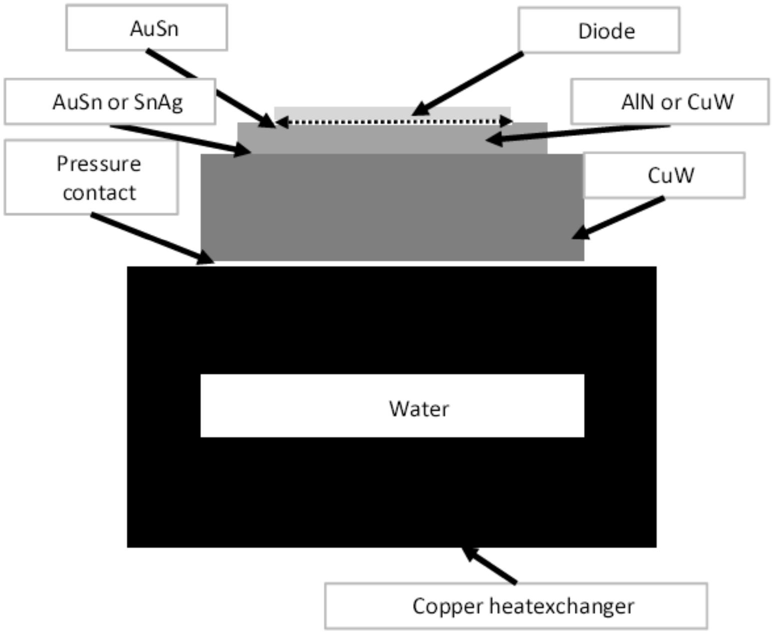




- Fused can be extended to beyond 20 inputs
- Proximity needs high brightness pumps

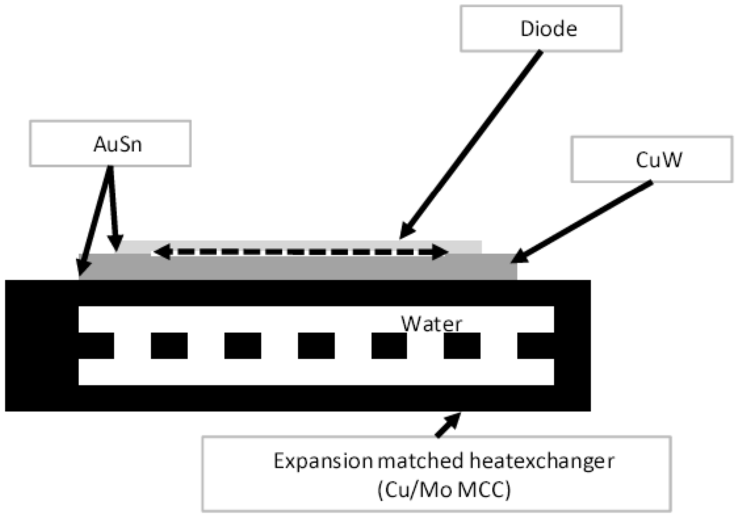
Broad Area laser Diodes
Single Stripe and Bar Wide

Passive Cooling

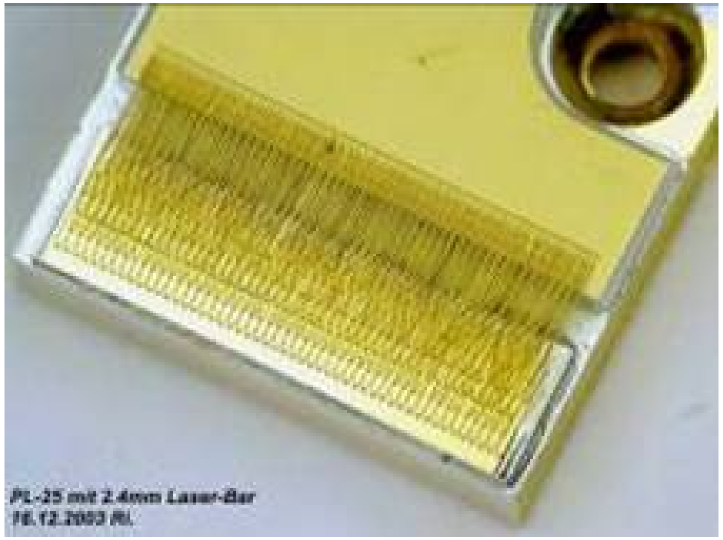


Cooling by heat spreading
Clamped to heatexchanger

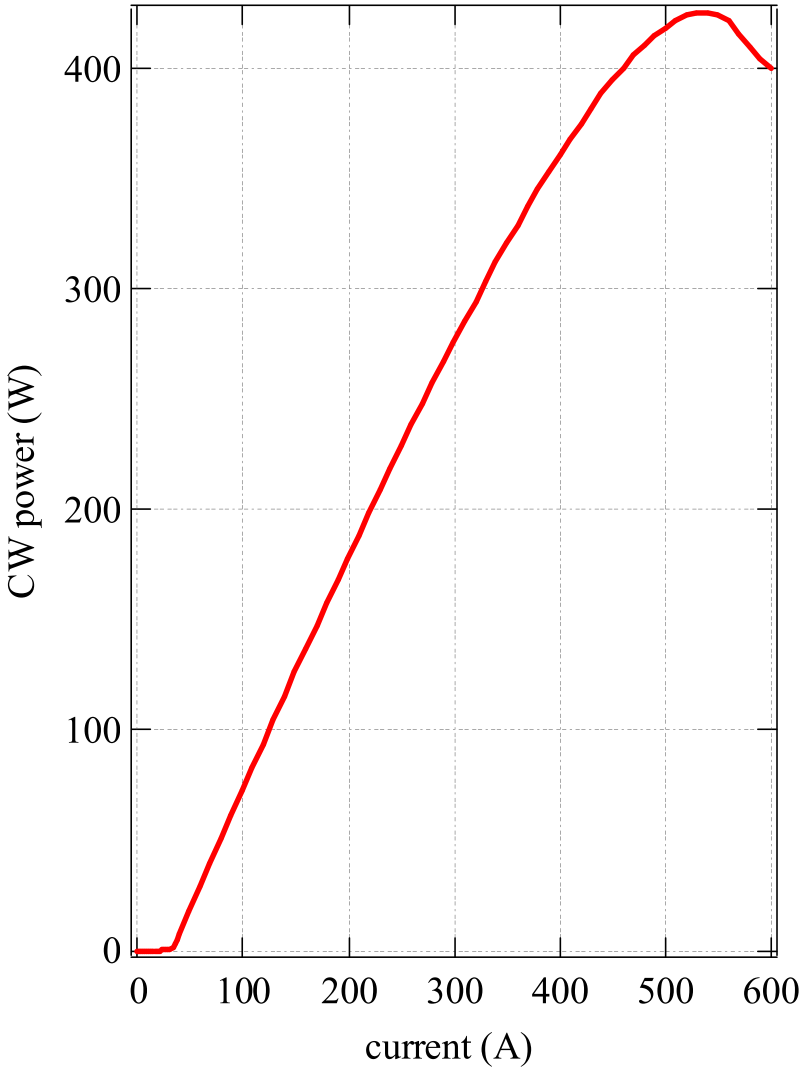
Active Cooling



Cooling by Mico-Channel Cooler
All AuSn soldered



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



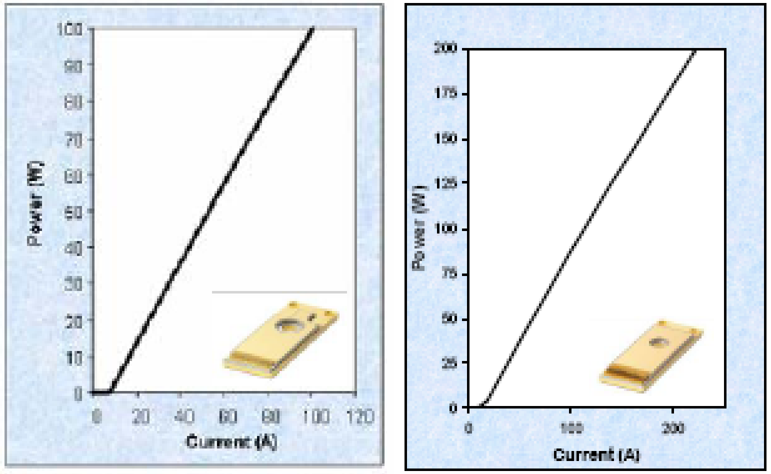
9xxnm 50%FF BAC Performance

Bookham

- **Electro-Optical**

– Power	80W	120W
– Drive Current:	87A	140A
– Threshold:	9A	14A
– Slope Eff.:	1W/A	1W/A
– Efficiency:	60%	60%
– LFF (90%PC):	7°	7°

P-I curves at 25C:

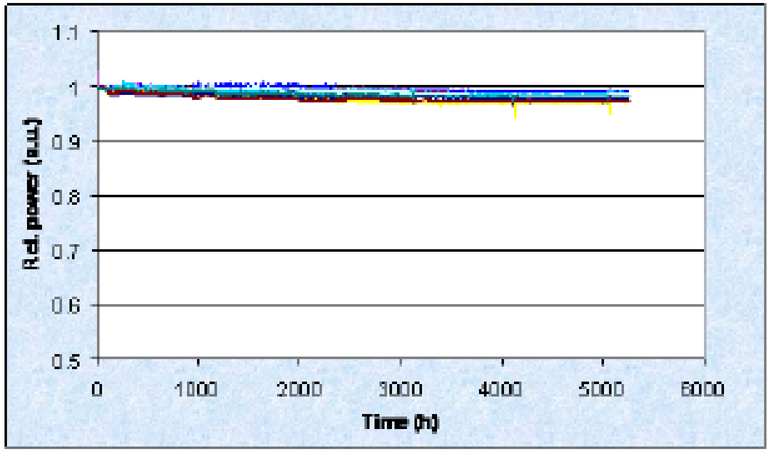


- **Reliability**

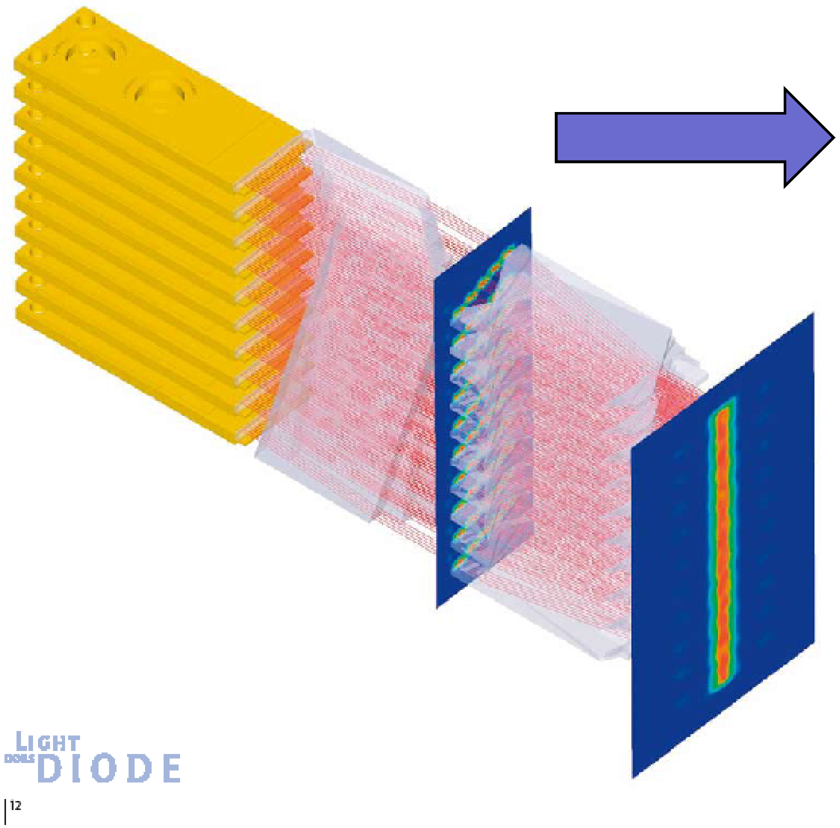
⇨MTTF >20'000hrs or >100 MCycles
(in accordance with ISO17526:2003)

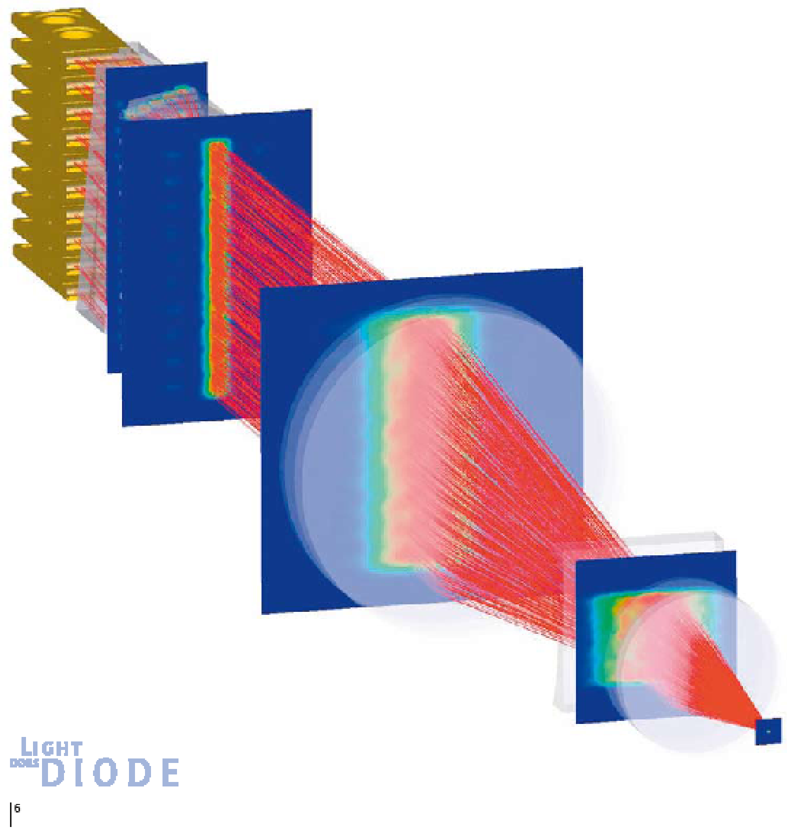
⇨Data available suggests for the semiconductor 80'000hrs or 350 MCycles
(less than 1% fails after 120 MShots)

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



Bar multiplexing to achieve highest optical power densities for direct application



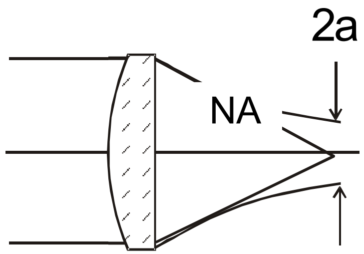


Picture with courtesy of laserline

Direct Coupled Diodes:

Laserline GmbH, Germany

Beamquality



Beam with aperture radius of “a” and divergence of “NA”

The beam parameter product is

– BPP=a*NA

The etendue (throughput)is

– Etendue=$(a*NA*\pi)^2$
  – or $a*b*NA_x*Na_y*\pi^2$ for an elliptical beam

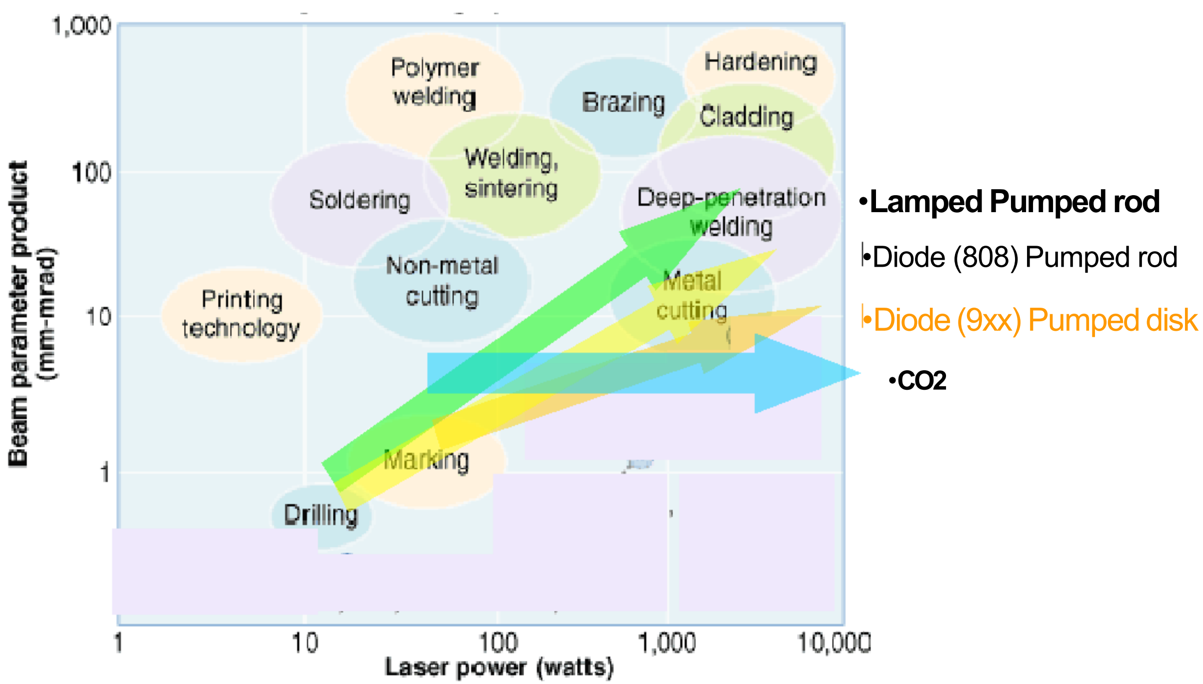
The minimum beam parameter product and etendue (corresponding to a single lateral mode) is given by

– BPP=a*NA=Lambda/ p =0.32um*rad for lambda=1um

– Etendue=$(a*NA*\pi)^2$=$Lambda^2$=$1*10^{-8}$ cm^2 ster for lambda =1um

A single mode 1 Watt laser yields 100MW/(cm^2 ster)

•Klassische Laser Strahlwerkzeuge



Source: P. Loosen, Fraunhofer Inst., Fuer Lasertechnik, Aachen, Germany

- Hybrid Laser Systems
  - Hybrid systems (Diodes, Lamps, Crystals, Dielectric Mirrors), Non hermetic cavity, Free space propagation
  - Beam limited by heat in active material
- Applications
  - Academia: Ideal for manipulation of beam
  - Industry: Delicate operation

Coupling Laser Diodes to a Fiber

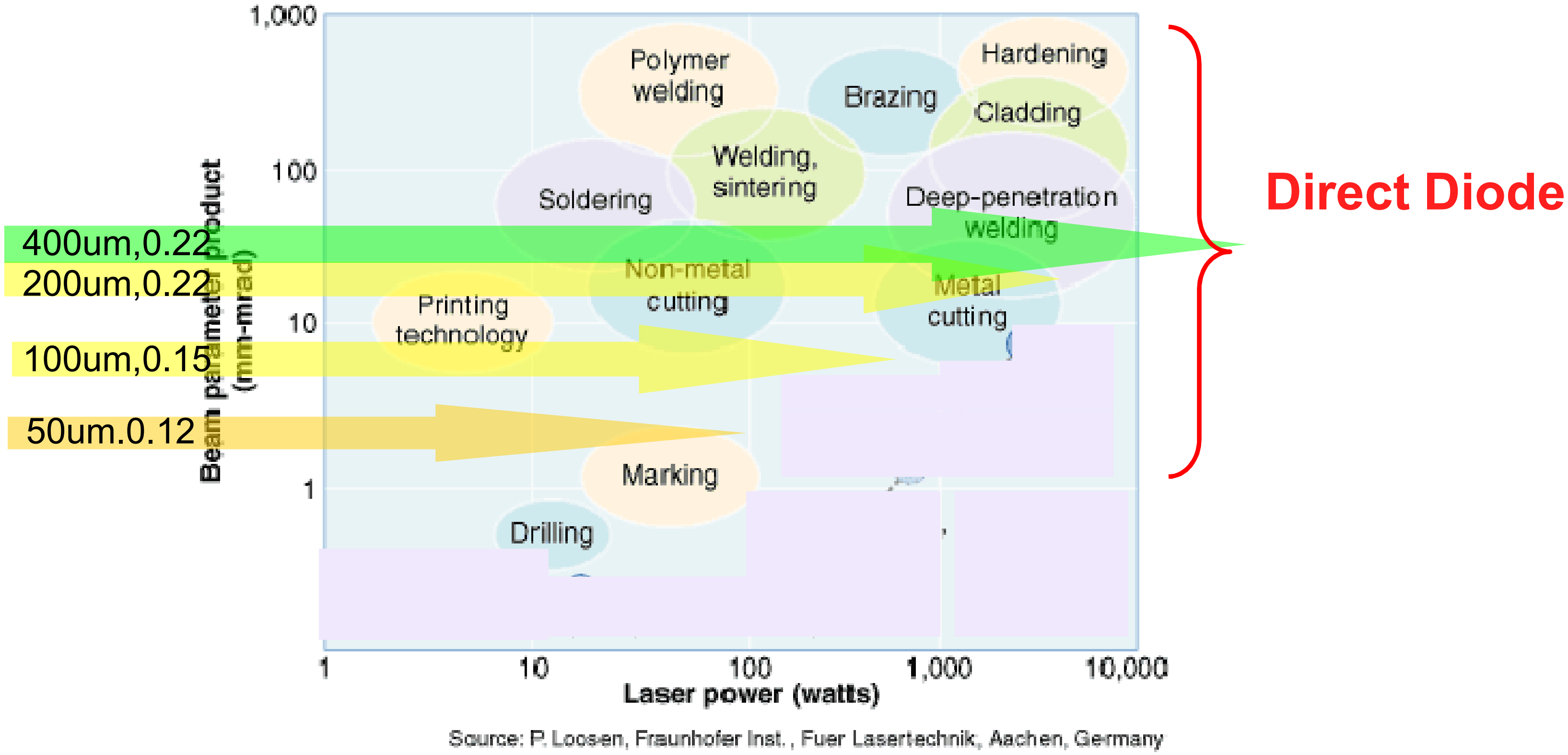
Diode Laser	Beam Width [um]	NA [rad]	Fast axis BPP [um rad]	Slow axis BPP [um rad]	Etendue [um² sr]
Single mode diode	5	0.12	0.3	0.3	1
Standard BA diode at low power	100	0.05	0.3	3	8
Standard BA diode	100	0.09	0.3	5	14
Low NA wide BA diode	200	0.09	0.3	9	28
Low NA minibar	3'200	0.07	0.3	112	340
Fiber	Core Diameter [um]	NA [rad]		BPP [um rad]	Etendue [um² 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

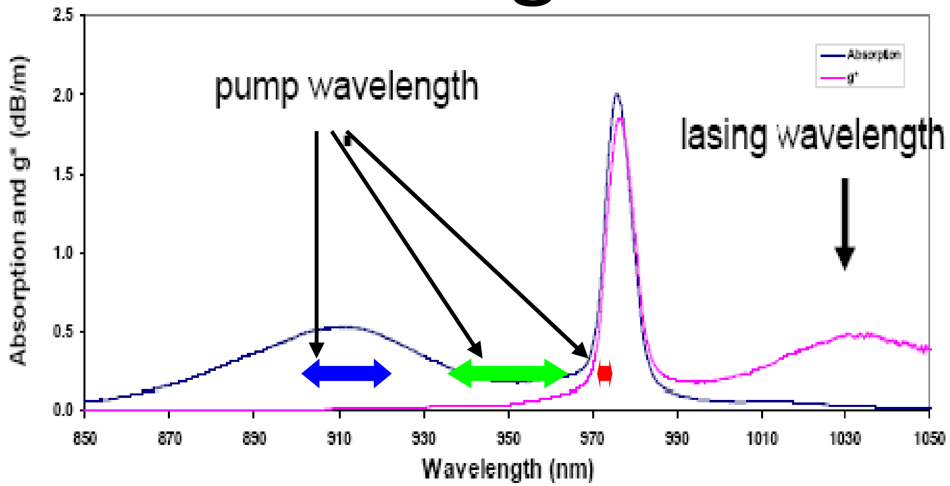
With polarization multiplexing and wavelength division multiplexing even mor diodes can fir in the fiber

Direct Diode Capability:



- Base of Arrow: Commercial, single wavelength, single polarization.
- Tip of Arrow: limit with single wavelength, single polarization (1W/mode)

Power Photonics
Yb fiber wavelength: 9xx bands



Yb: Glass fiber absorption and emission spectrum

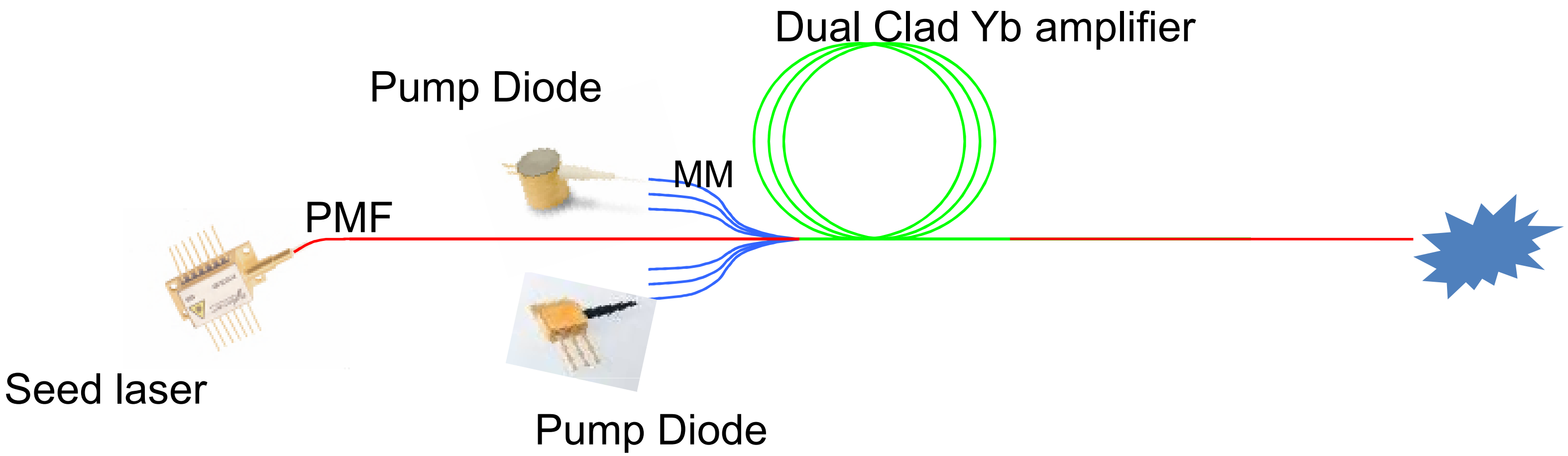
Wide pump band: 870nm to 980nm

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

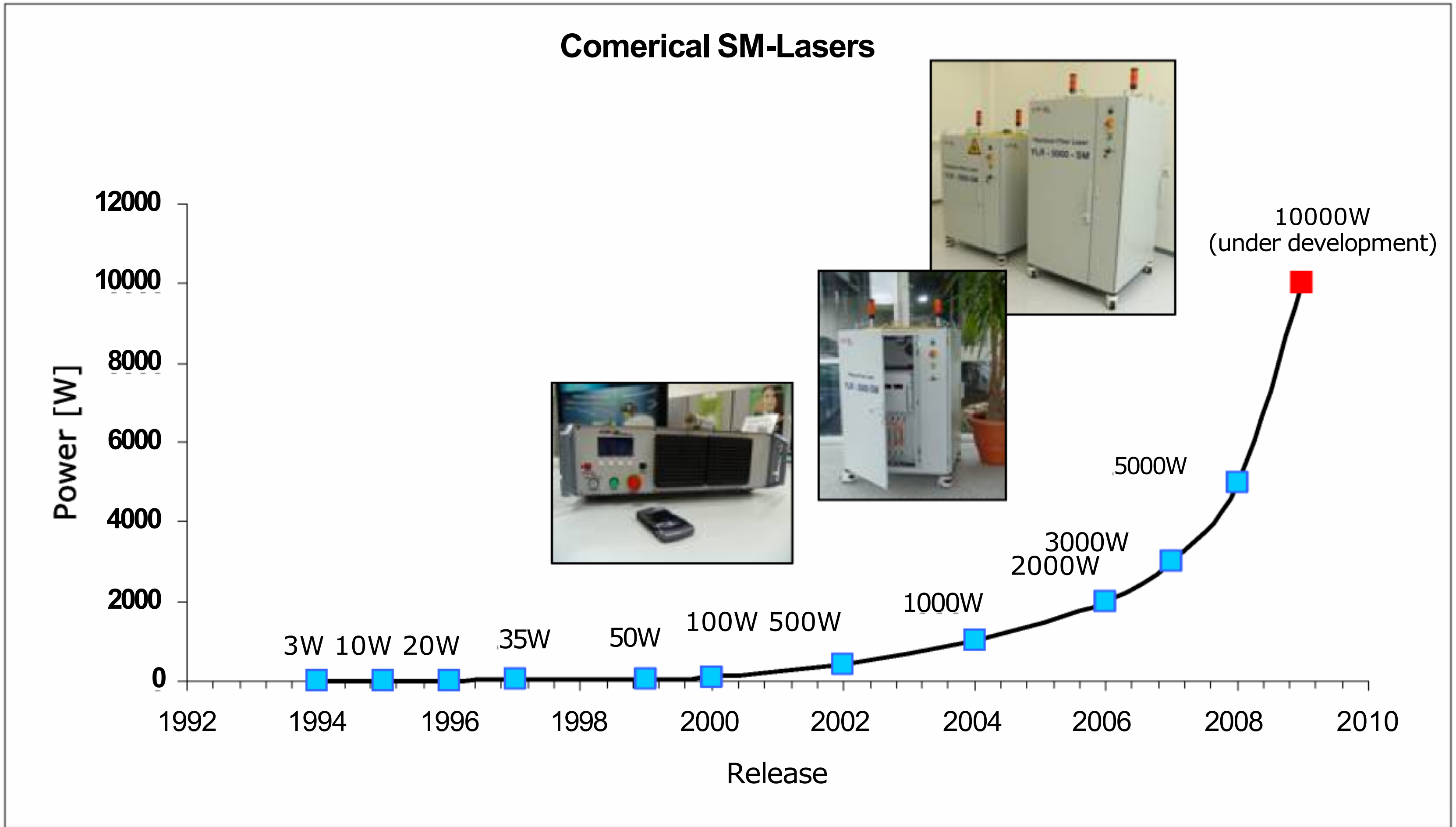
Red band (976nm)*: Highest absorption, narrow width*
- *Preferred for high gain amplifiers and q-switched lasers with short fiber (SBS)*
- *Pump diode challenge: Diode wavelength control (+/-2nm) necessary*

Power Photonics
Fiber "Laser"= Fiber MOPA

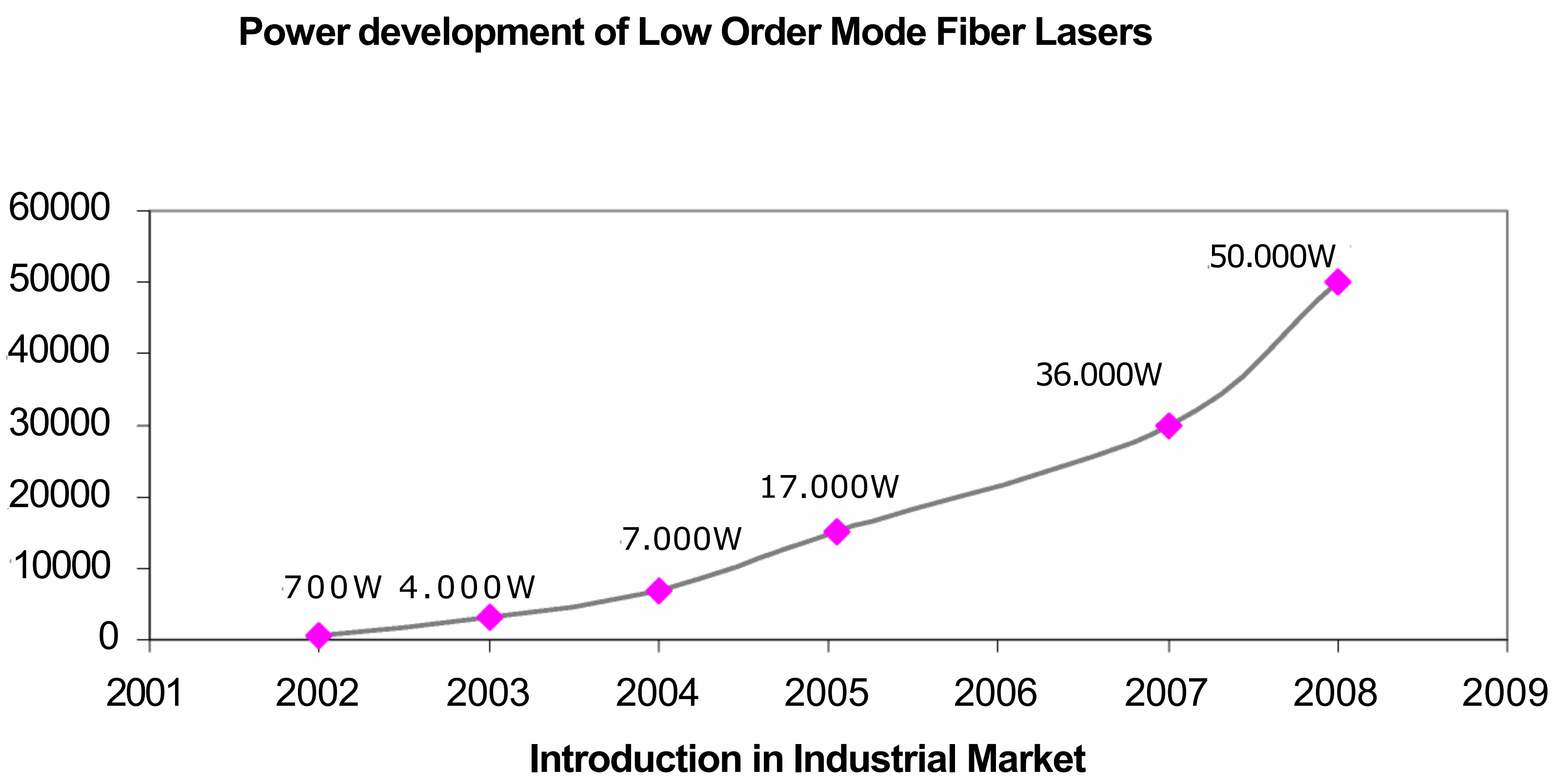


- Seed laser
  - Fiber laser: Good spectral control
    - Need external modulators (Pockels Cell)
  - Diode laser: Excellent dynamic control
    - FP laser have poor spectral control, of no concern
    - DFB have excellent spectral and dynamic control
- Pumplaser
  - Single emitter broad area MM diode

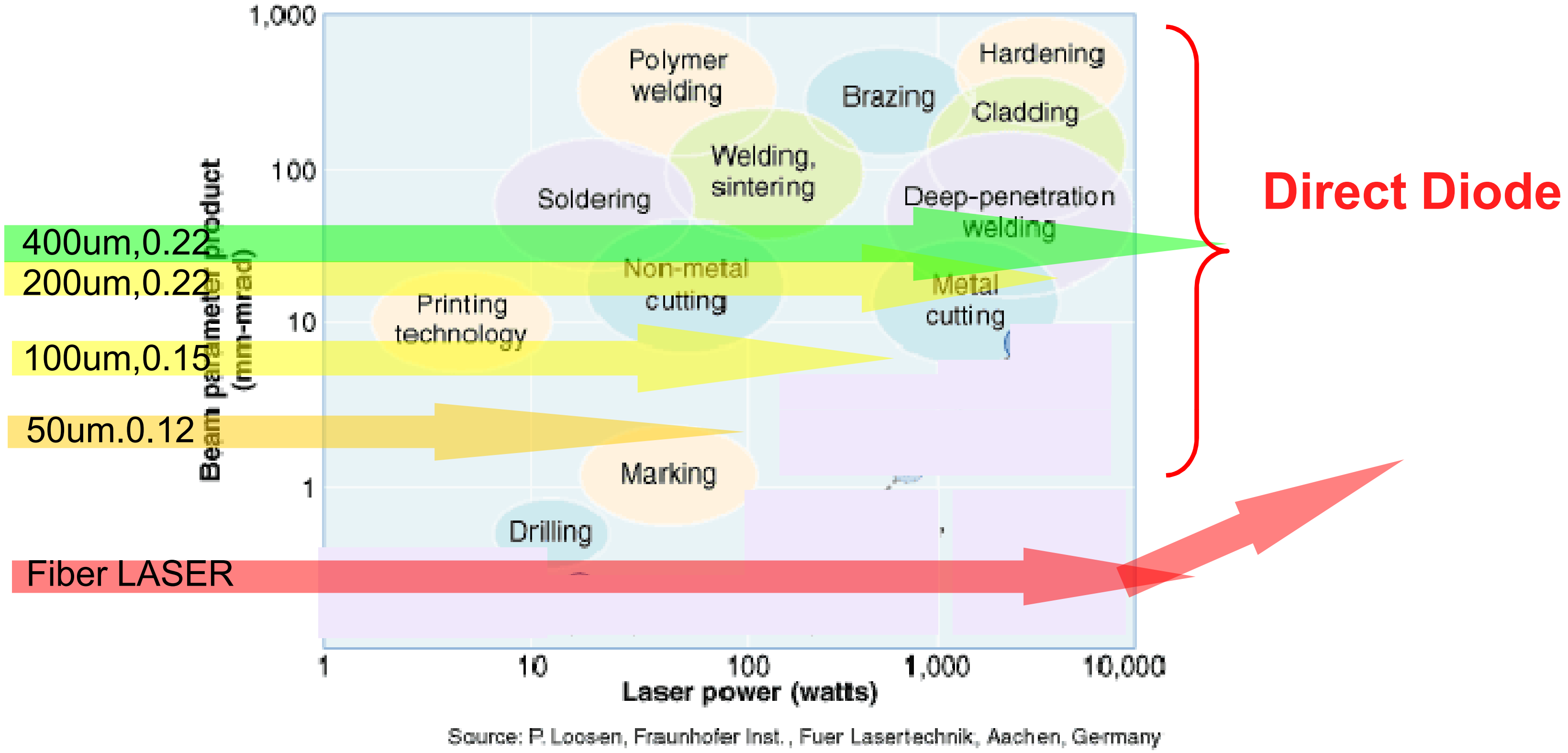
Status and Development of Single Mode Fiber Lasers



High Power Fiber Lasers - History



Direct Diode Capability:



Source: P. Loosen, Fraunhofer Inst., Fuer Lasertechnik, Aachen, Germany

Reduce Cost of coupling diodes to the fiber

Base of Arrow: Commercial, single wavelength, single polarization. Tip of Arrow: limit

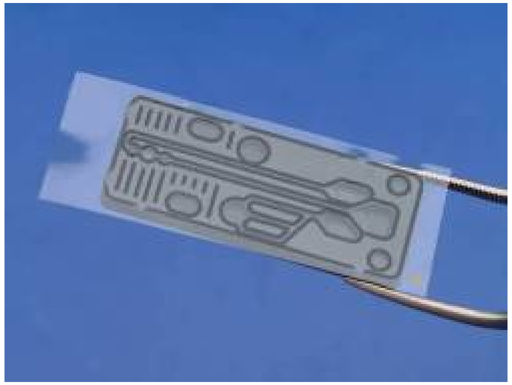
Application example: welding of thin foils

Foils

-Polypropylen (PP) transparent and black thickness 100 µm

Microfluidic device

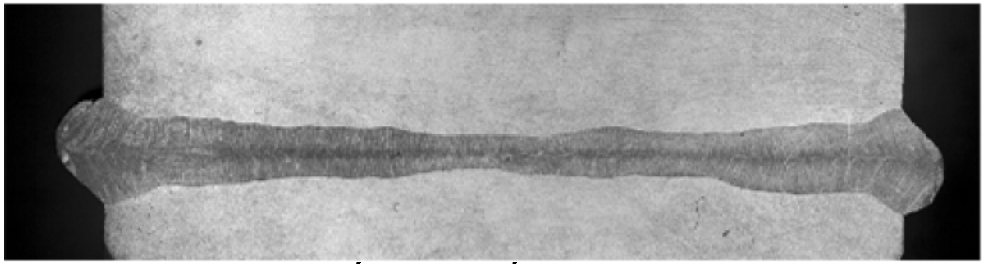
- PMMA or PP sealing foil (75 µm)



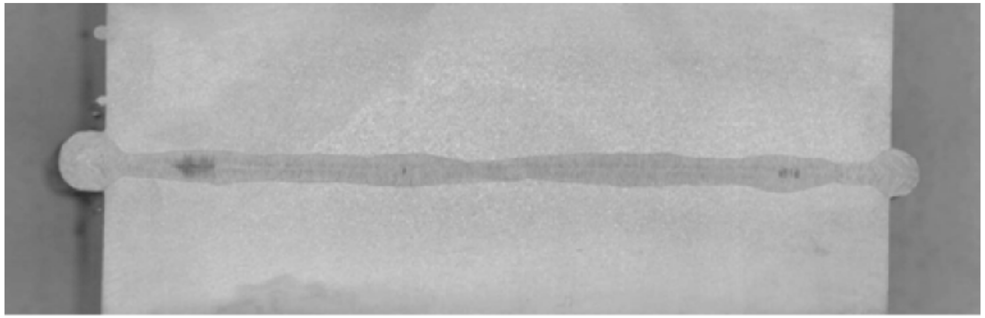
P= 1,4 – 5,9 W
v= 50 to 250 mm/s
d_0= 70 µm
$d_{weld\ seam}$= 150 to 500 µm

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:

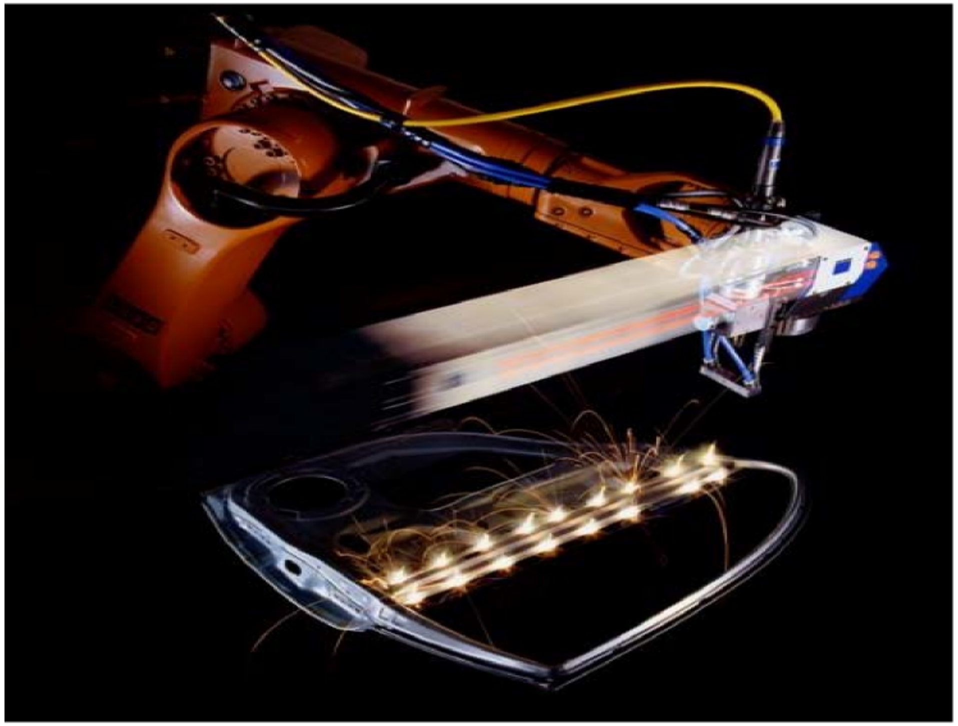
Laserinstitut Mittelsachsen e.V.

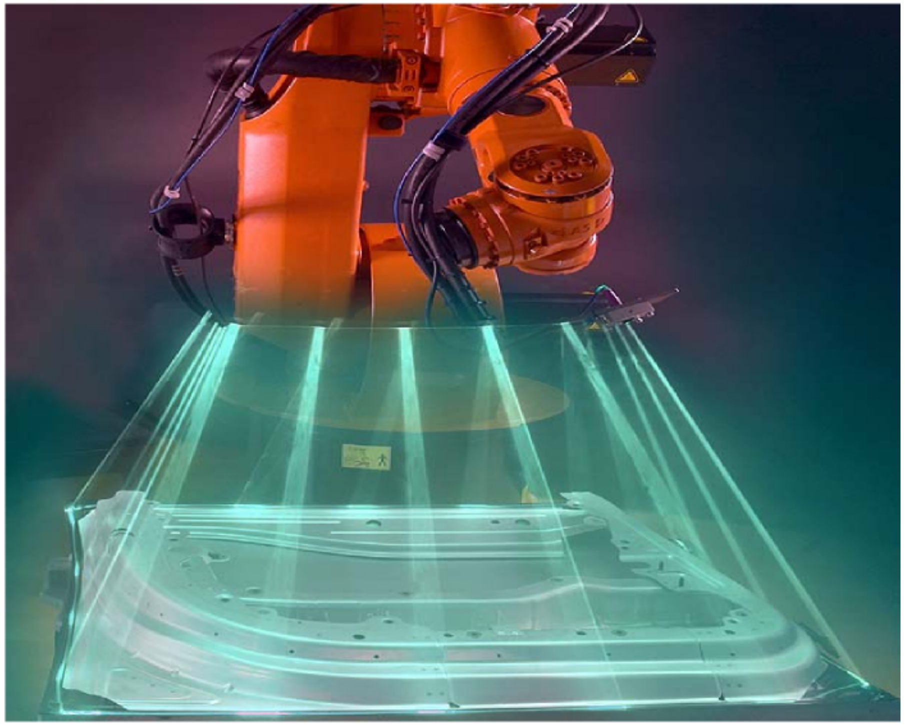
IPG PHOTONICS

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

Bewertungskriterien:

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

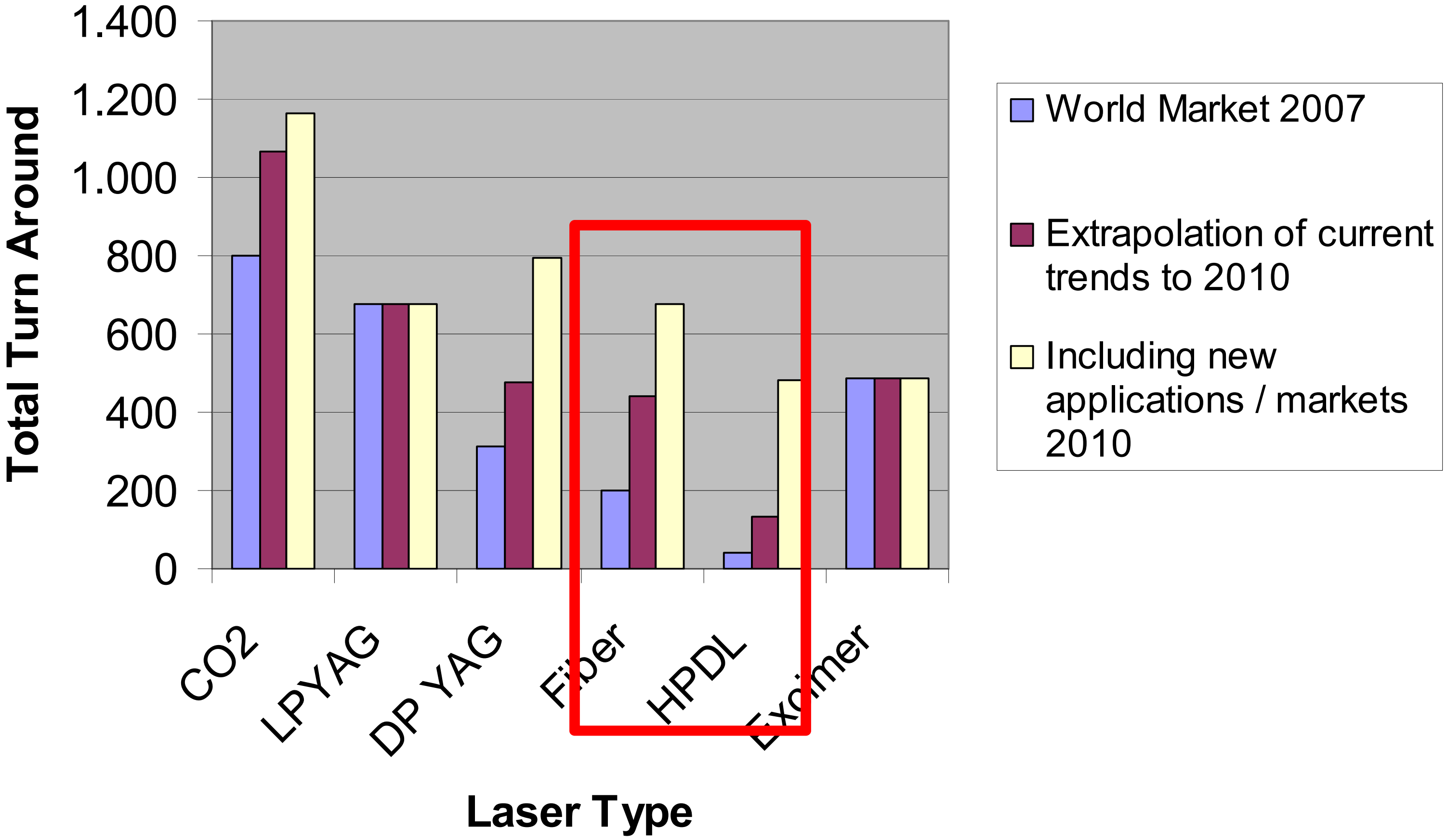




Assessment criteria:

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

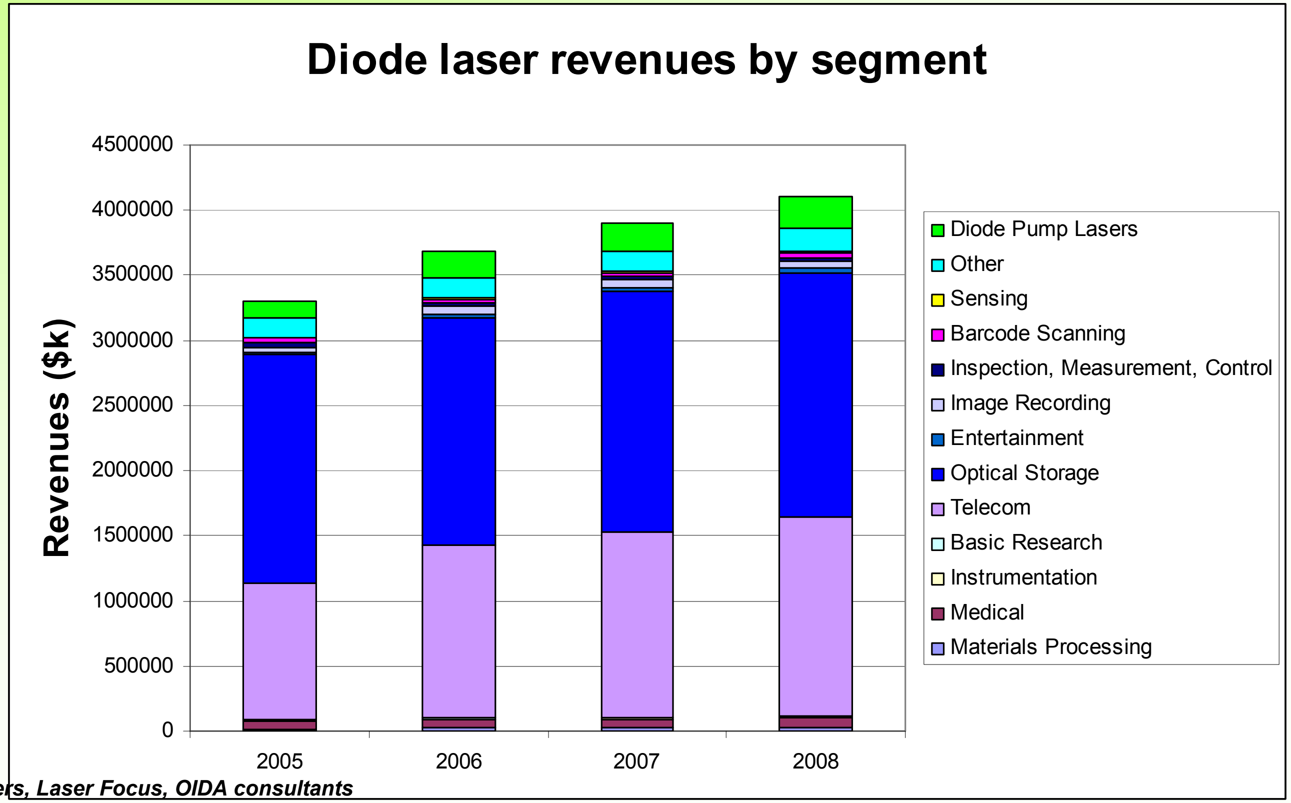
Power Photonics



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

Diode laser revenues by application

- Diode pump lasers grow faster than rest



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

Michael Lebby
(lebby@oida.org)

Where is the new cash cow?

Direct Diode: Trends

- Power Photonics, all solid state based high power sources will grow much faster than the market.
  - Based on pump diodes, fiber combiners and couples, passive and active fibers
- Classic lasers CW lasers around 1 um (lamped pumped and diode pumped YAG lasers) will be displaced
  - Supperior efficiency of direct diode (50% wallplug power conversion) and fiber lasers (30% wallplug power conversion)
- High cw powers will enable new applications (3d cutting, ..)
- Classic lasers (C02, excimer, ultrashort pulses) will continue to be used based on wavelength and high peak power/short pulse length