High-Power Laser Diodes

Christoph S. Harder

Harder&Partner
charder@swissonline.ch

+41 79 219 9051

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High Power Laser Diodes

1. Single Mode Pump Lasers
   - EDFA: Killer application
   - Drove Technology to Maturity in 10 years

2. Beam Machining Tool
   - Fiber laser: Pump lasers
   - Direct Diode

- Acknowledgement
  - Dr. Berthold Schmidt, Bookham
  - Dr. Toby Strite, JDSU
  - Prof. Ursula Keller, ETH
  - Prof. Amos Hardy, Technion
  - Dr. Martin Achtenhagen, EPFL

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'

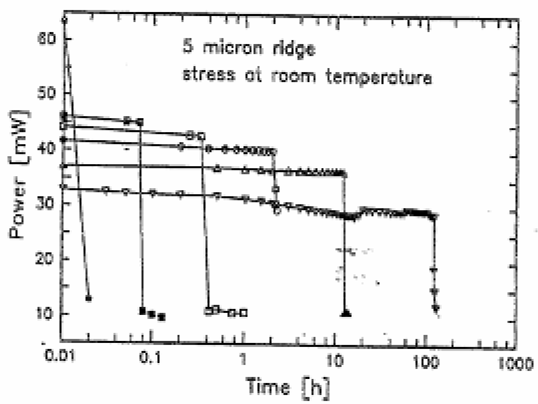
Never achieved reliable beamstability for high volume applications

- Investigate COMD in 80's for InGaAlAs lasers for
  - MO storage
  - Computer Interconnect

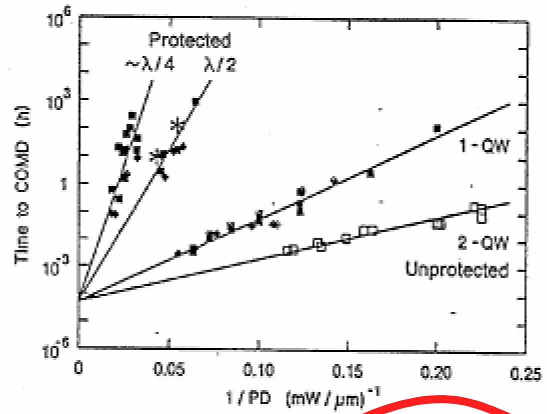
Time to COMD: 20 years ago

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

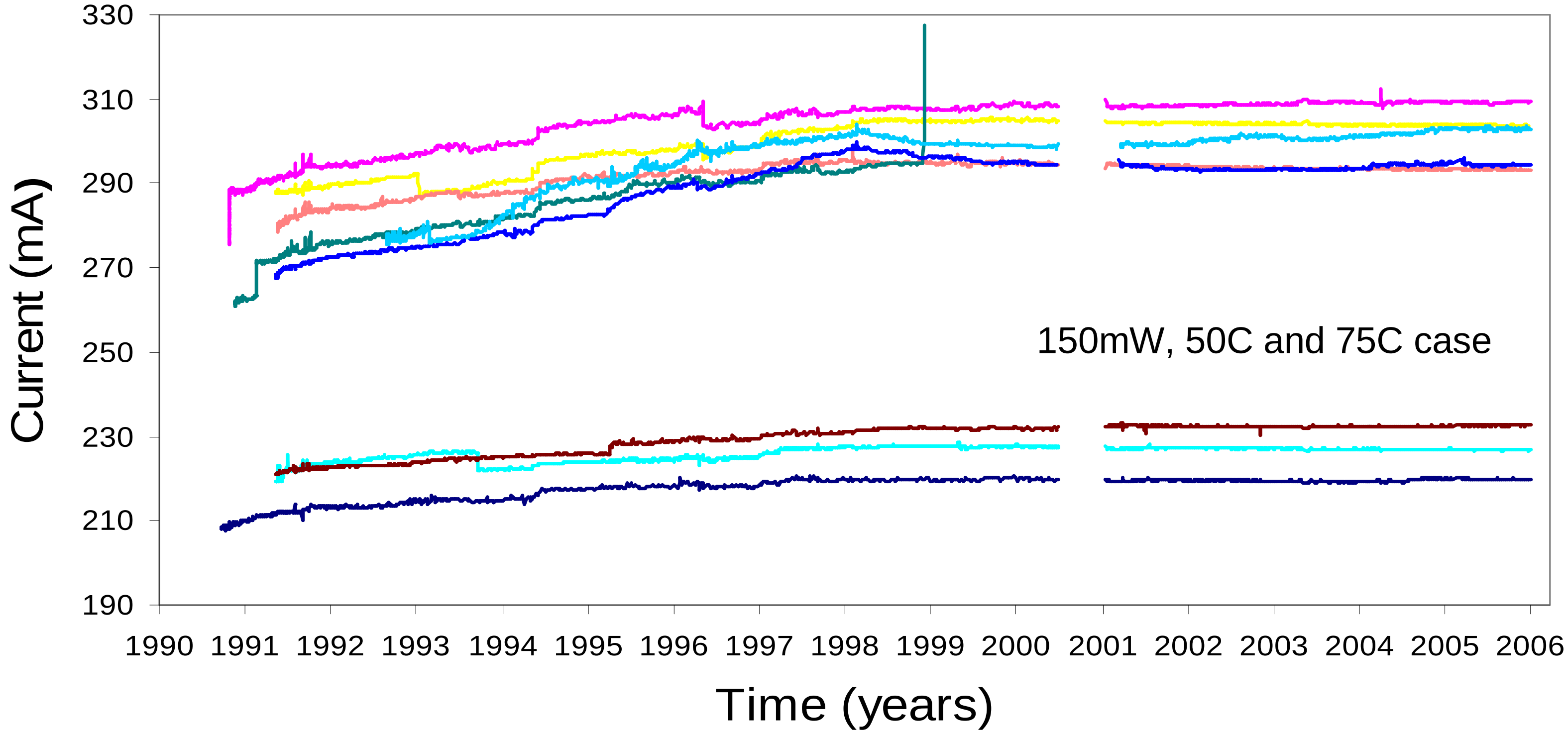
Solved in 1987 (E2)

OSA_91

IBM

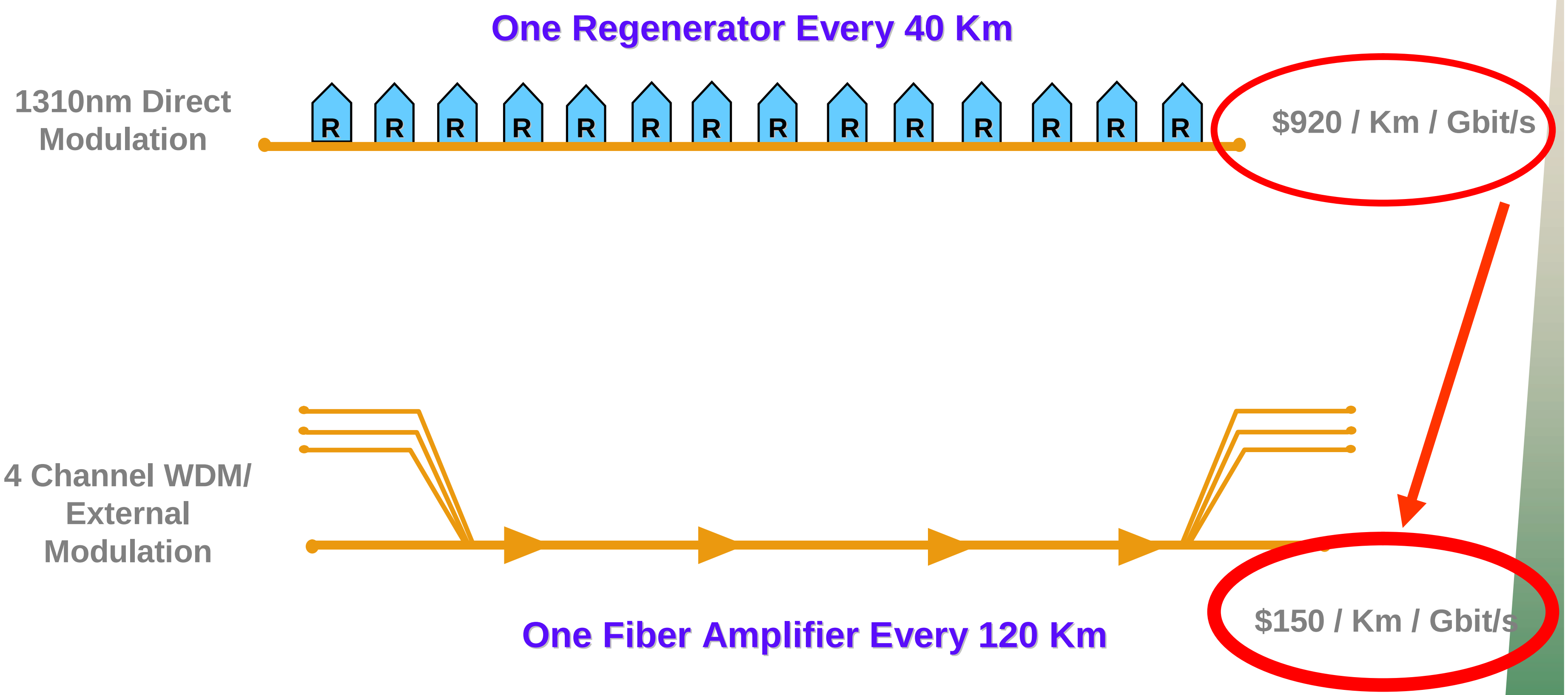
11/91 (Ch. Harder)

E2 passivated 980nm pumps



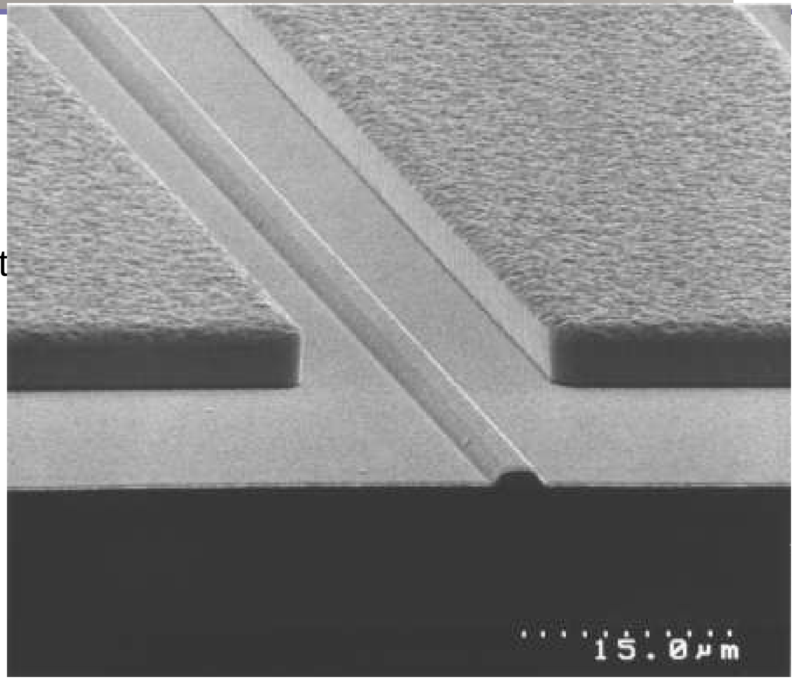
- In 1990 started again 9 lasers (Corning had approached us for 980nm EFA pumps).
  - EDFA: Killer application drove technology quickly to maturity
  - 8 of 9 are still alive after 16 years

External Modulation Enables Cost Reduction



JDS Uniphase

Single Lateral Mode Laser: Ridge Waveguide



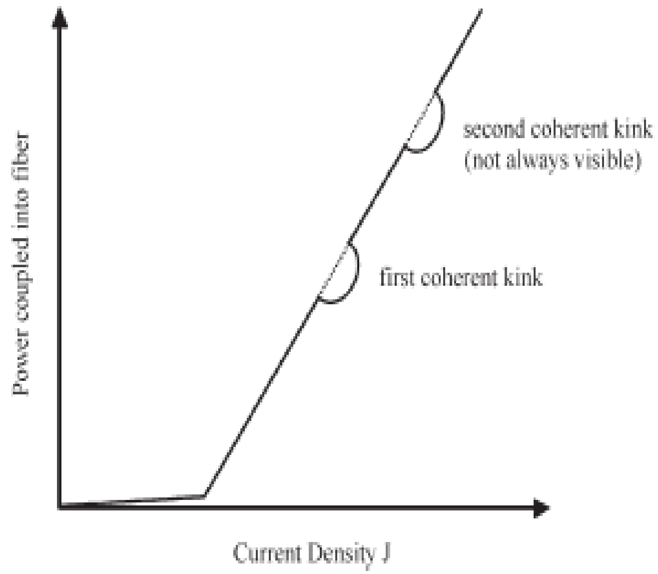
Ridge Waveguide

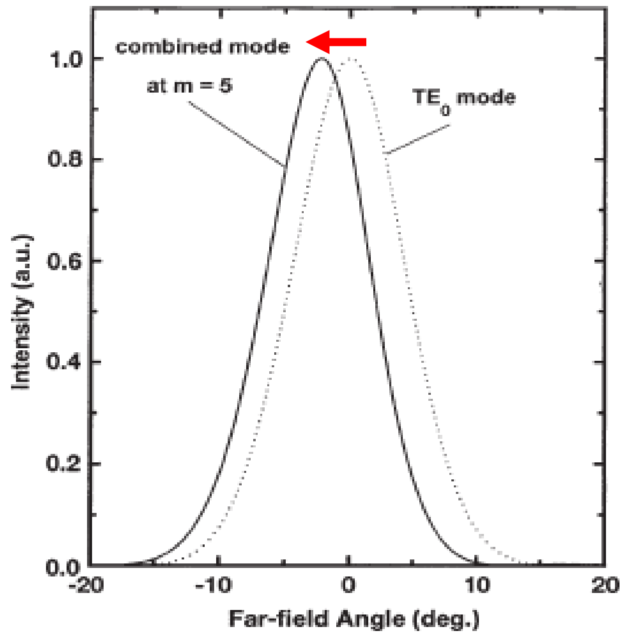
- Index guided mode
  - Excellent coupling to fiber
  - Temperature insensitive current confinement
  - High linear power
- Low loss waveguide
  - Increase power by making chip longer
- Low temperature process
  - Reliable
  - No regrowth
- Material
  - InGaAlAs for best material properties

Widespread

- ~2‘000‘000 pumps based on this technology shipped, 50% terrestrial and 50% of intercontinental (submerged) internet is powered up by these pump technology
- Submerged systems: No fail of consequence

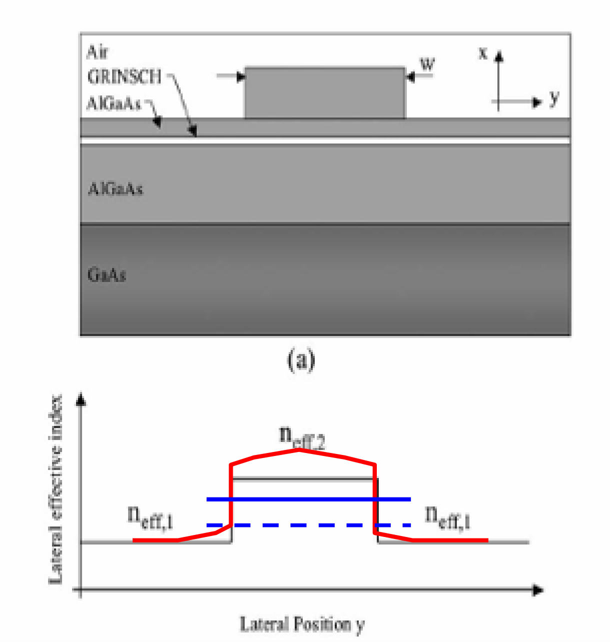
‘Shift’ Kink: Observation



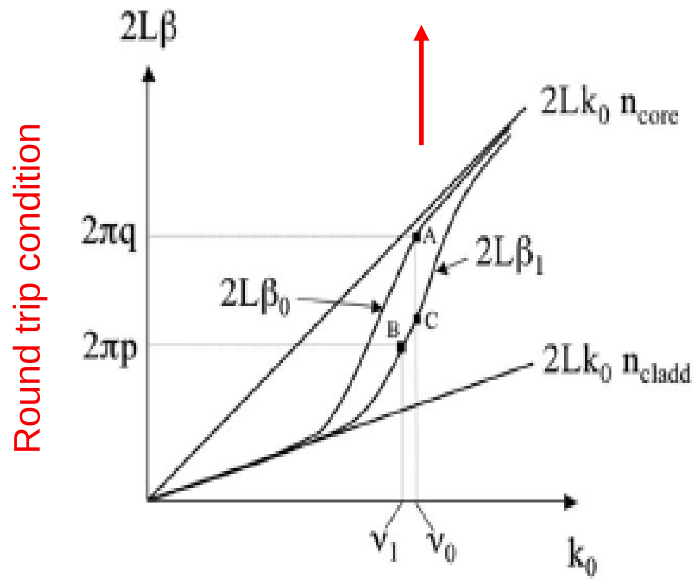


- Observation (1991)
  - Sudden kinks in fiber coupled power
- Standard countermeasure:
  - Increasing loss for higher order modes (to keep them below threshold): Does not work
- Farfield observation
  - Still single ‘humped’, but shifted during kink

Shift Kink: Waveguide Dispersion



Index moving up with temperatureprofile (drive current)

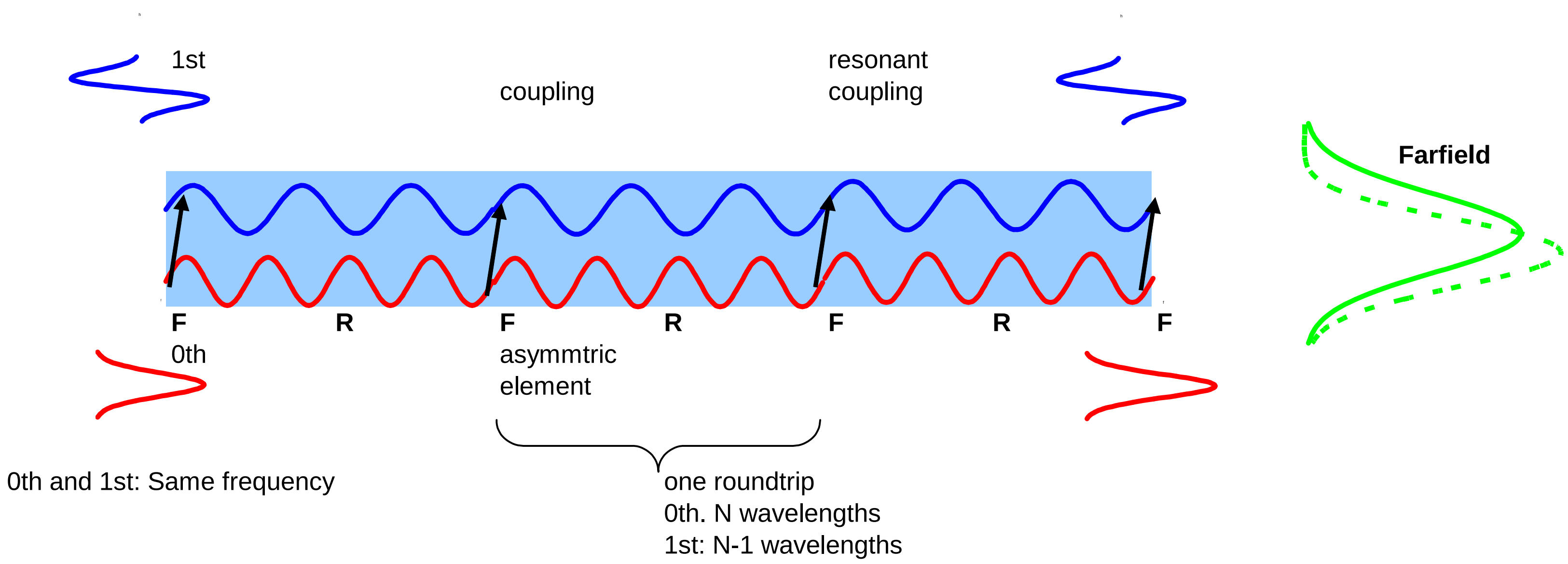


For $\upsilon_1 = \upsilon_0$

Coherent coupling

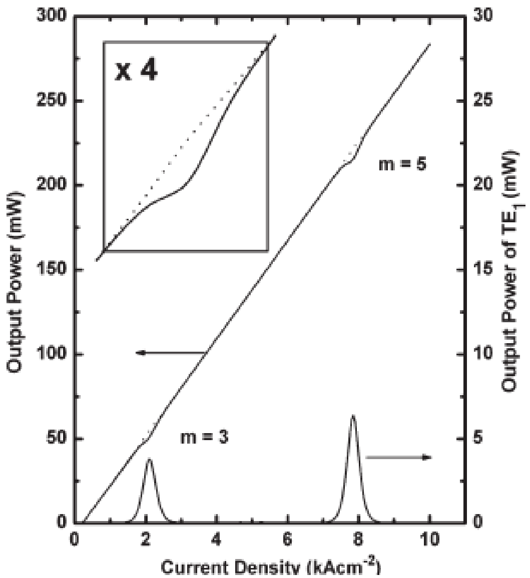
- Waveguide
  - Index increases with local heating
  - Waveguide becomes multimode
- Dispersion characteristics of waveguide
  - Phase lasing condition (integer number of wavelengths in one roundtrip) can be meet for one frequency (**$\upsilon_0 = \upsilon_1$**) for fundamental and higher order modes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

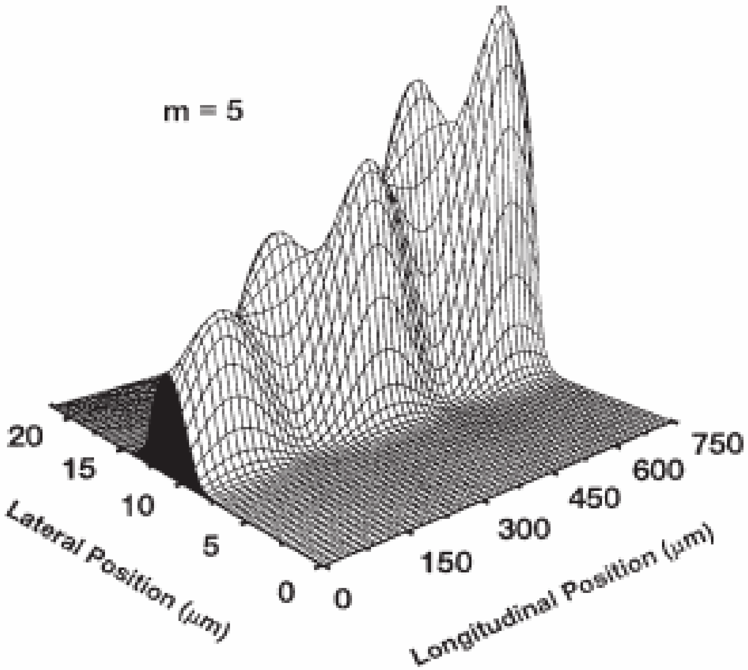
Shift Kink: Coherent Coupling



- 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. current)
  - ‘lateral mode locking’ at this current

Shift Kink: Lateral Mode Locking



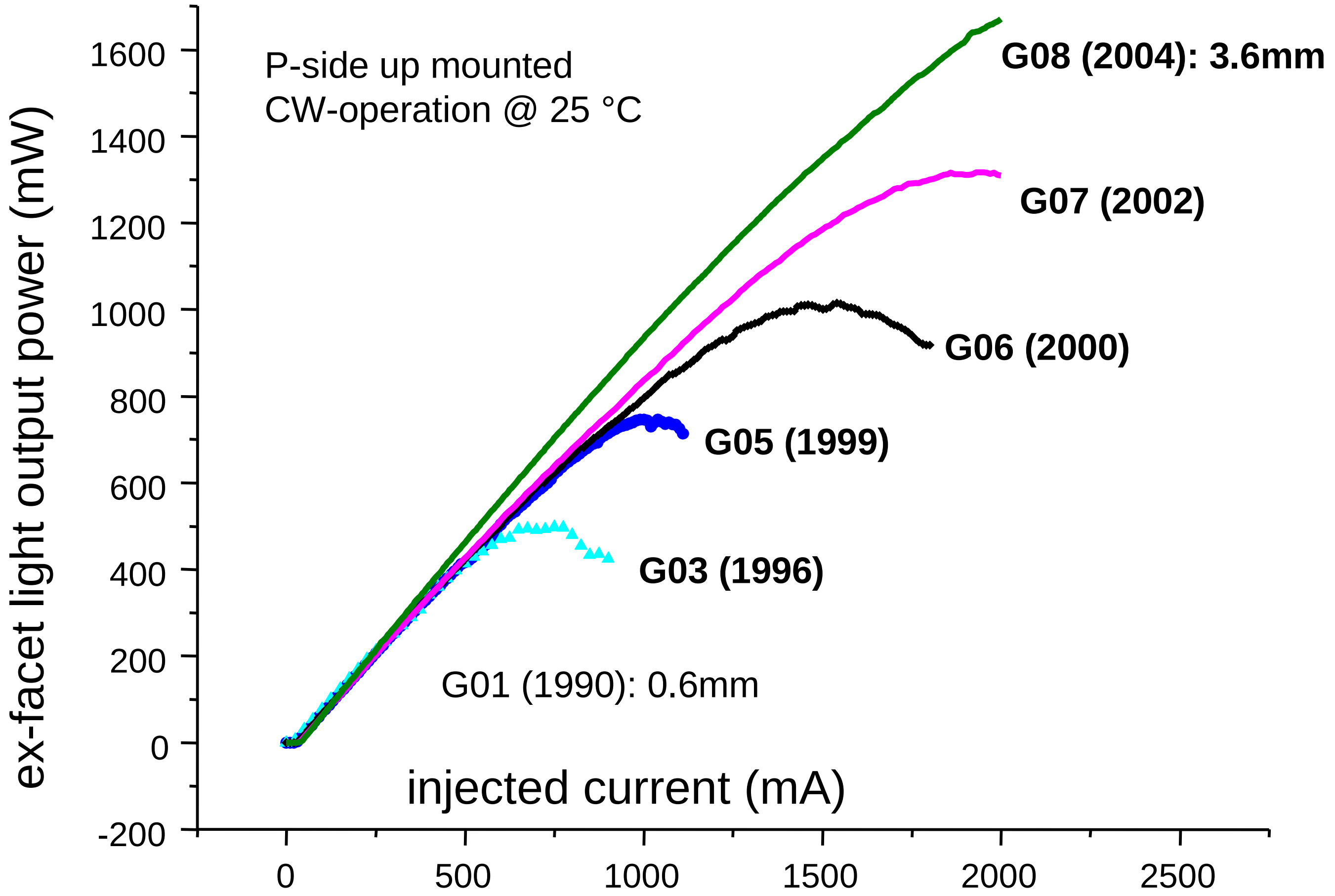


Coherent coupling, lateral mode locking

- Power gets coherently coupled (only one lasing frequency) away from fundamental mode into higher order
- Locking range
- Interference within waveguide

Achtenhagen, Hardy and Harder, JQE Vol24 pp2225

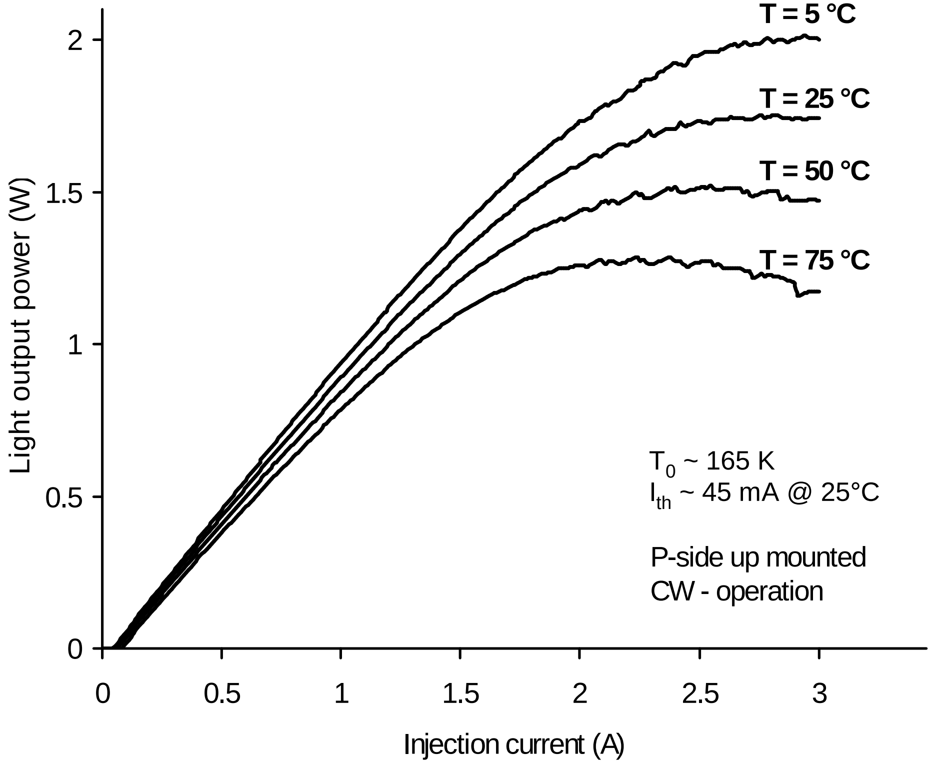
Length Scaling



Improve performance by making laser chip longer

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

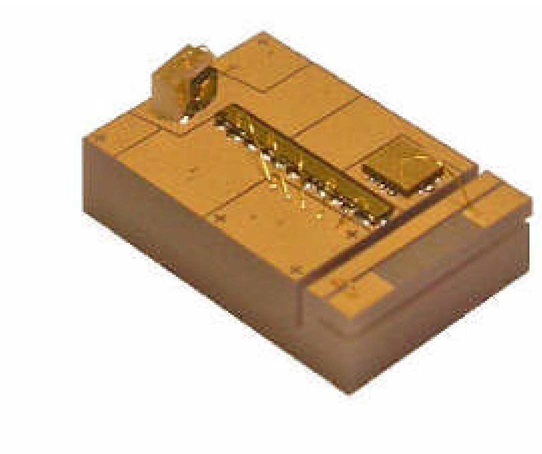
980nm single mode pump chip: 2004

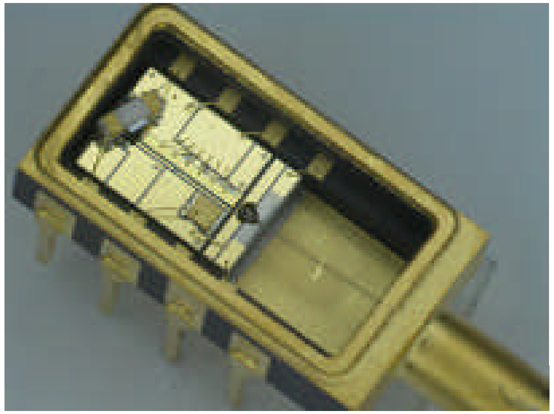


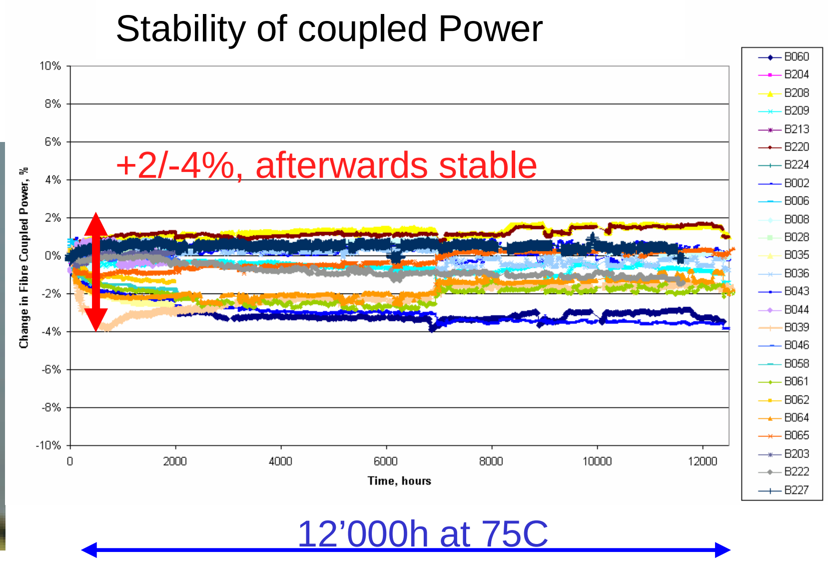
150MW/cm2

- 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

Low Cost High Performance Packaging: 2004

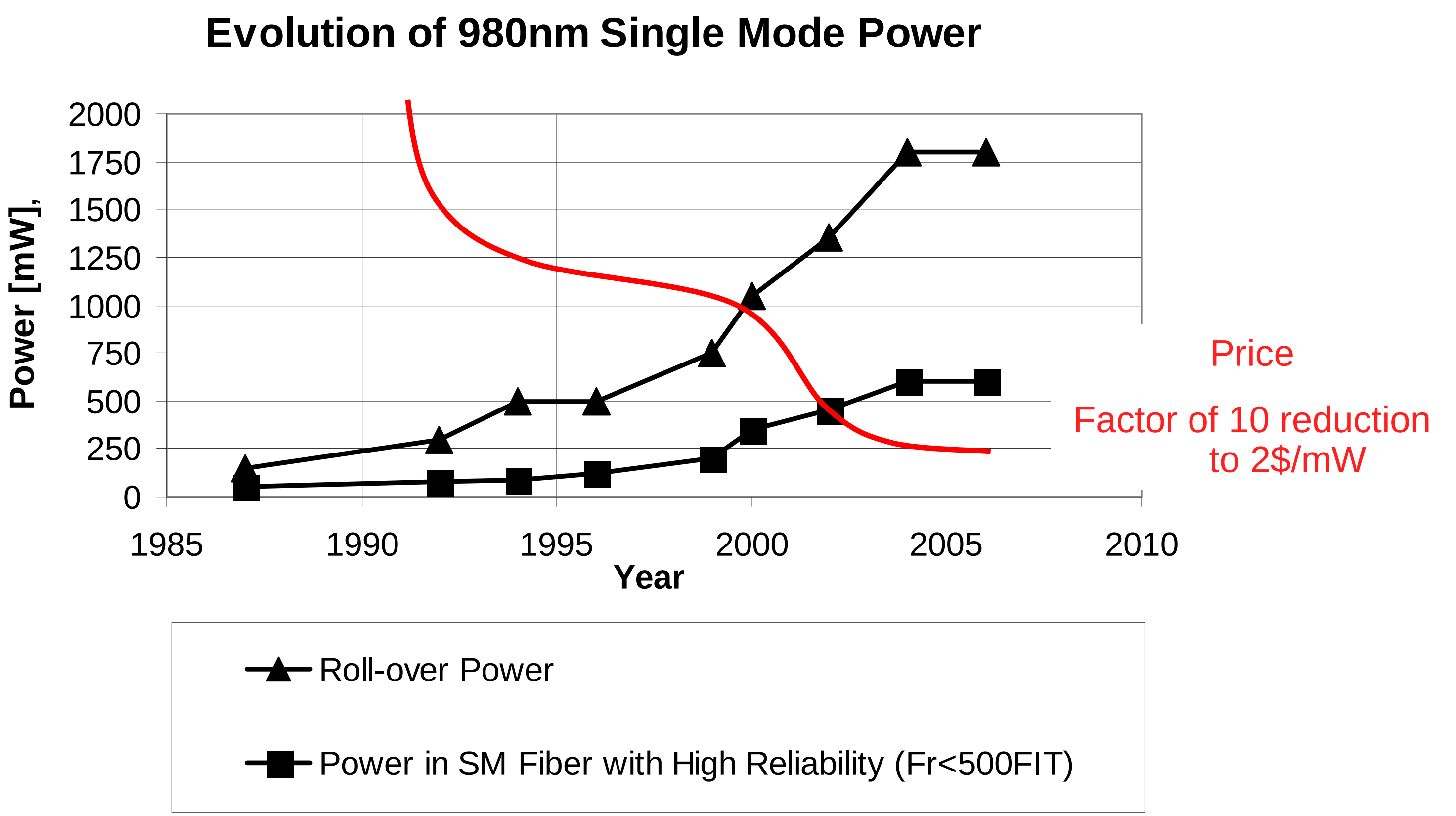






- Performance (Commercial Products)
  - 200mW uncooled MiniDIL (-5C to 75C) with telcom reliability
  - 600mW Peltier stabilized BTF with telcom reliability

EDFA Pump Power Development



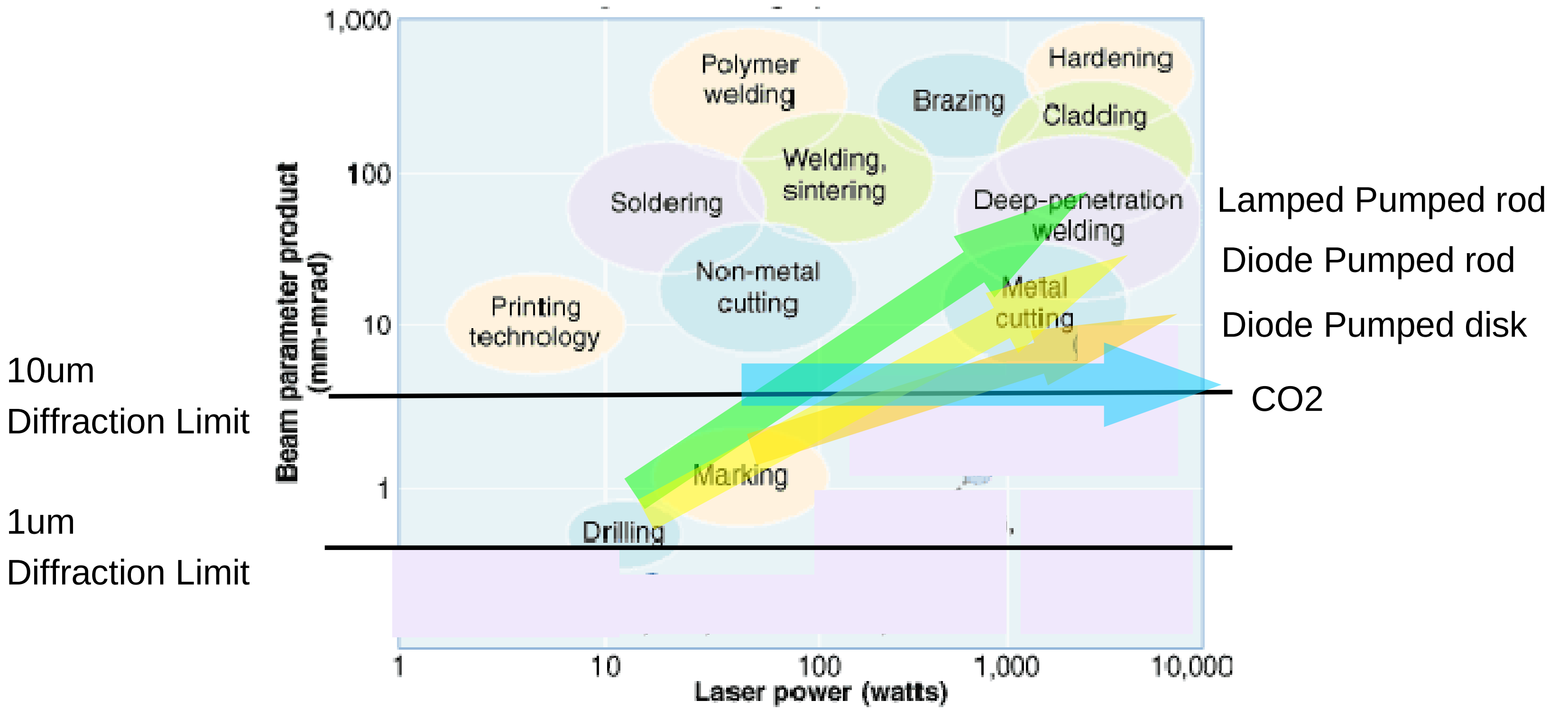
EDFA pumps: Matured

-> Power increase stopped

-> Cost reduction done

-> Spectral stability and noise done

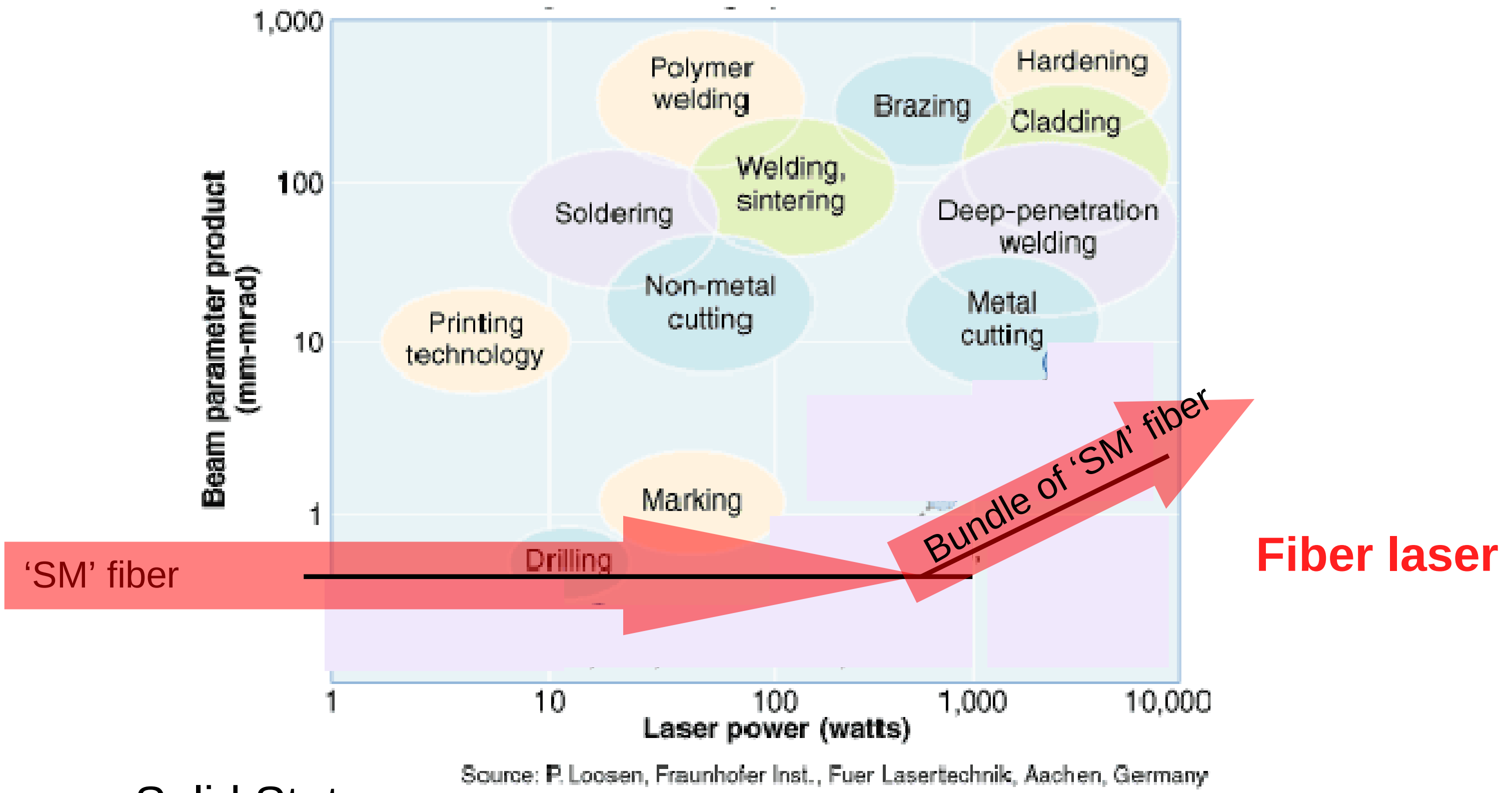
Classic Laser: Beam Machining Tool



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

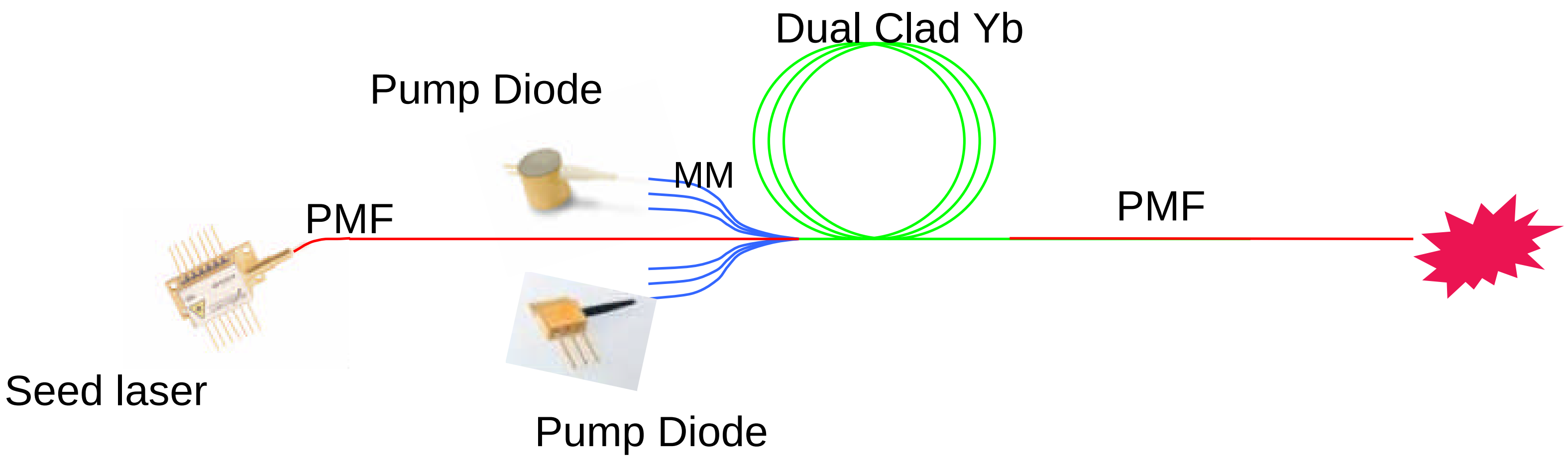
- Hybrid Laser Systems
  - Hybrid systems (Diodes, Lamps, Crystals, Dielectric Mirrors), Non hermetic cavity, Free space propagation
  - Beam limited by heat in active material
- Applications
  - Academia: Ideal for manipulation of beam
  - Industry: Delicate operation

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

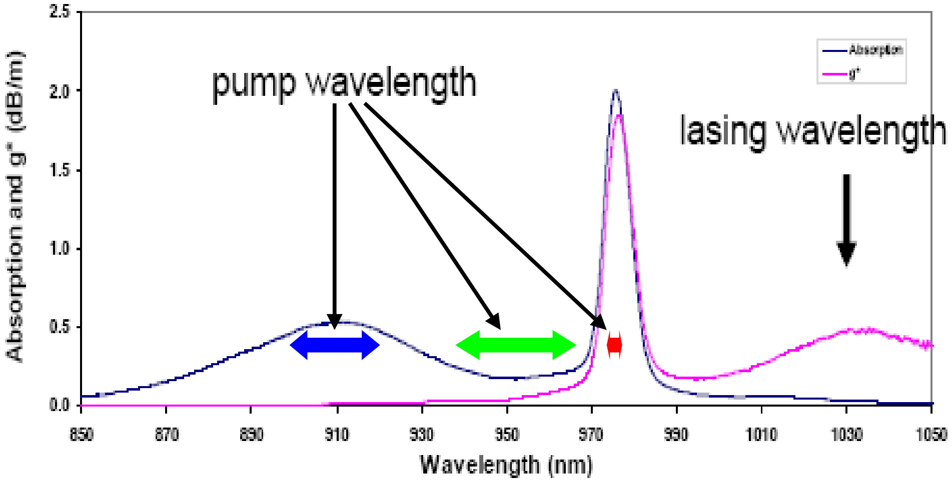
Fiber Laser: MOPA



- 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

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*

Fiber combiner
Fused and Proximity

Fused: (6+1)*1

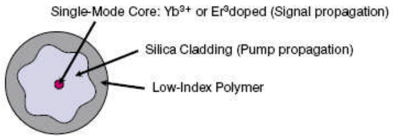


Figure 2 **Cross-section of double-clad optical fiber for cladding pumping.**

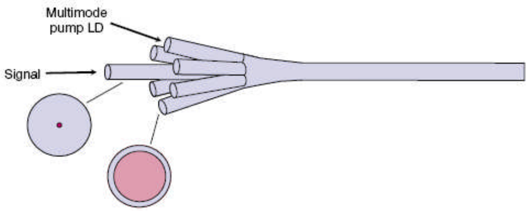
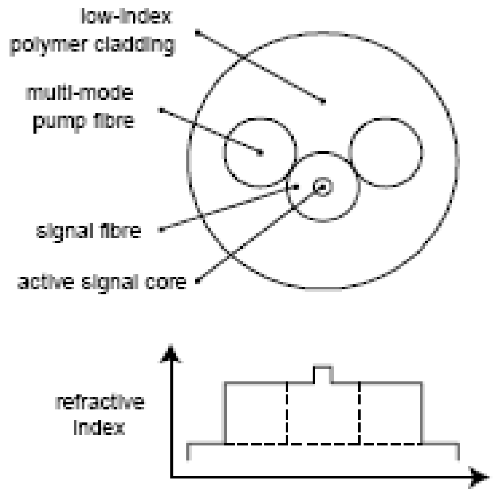


Figure 3 **Schematic of tapered fiber bundle.**

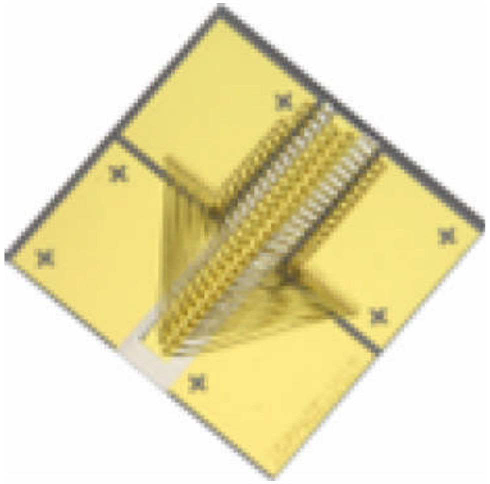
	Fiber	NA
Signal input	HI 1060	
Pump Ports	6*105um	0.22
Output	20um/400um	0.06/0.46

Proximity: (2+1)*1

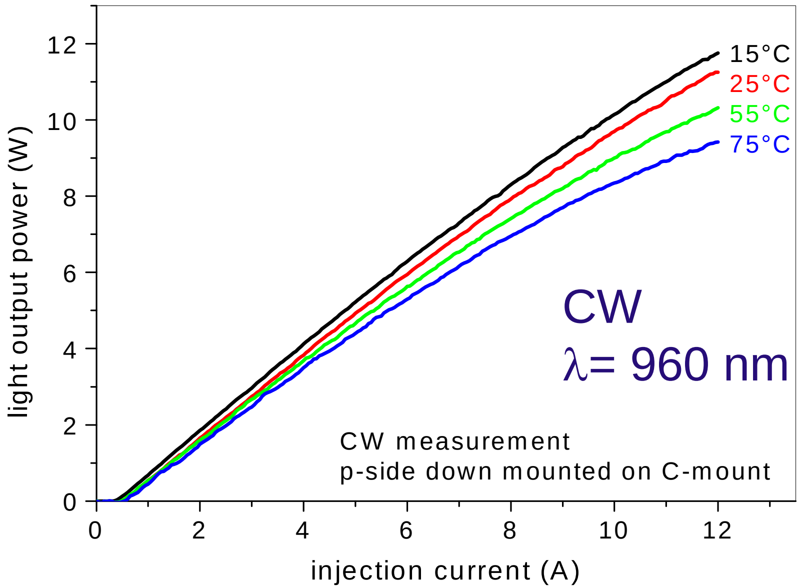


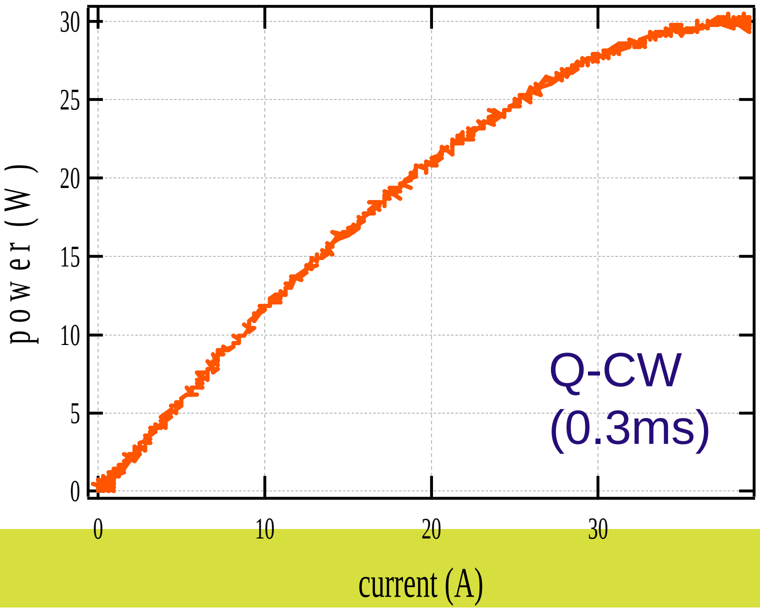
- Fused can be extended to beyond 20 inputs
- Proximity needs high brightness pumps

SES8-9xx-01 performance



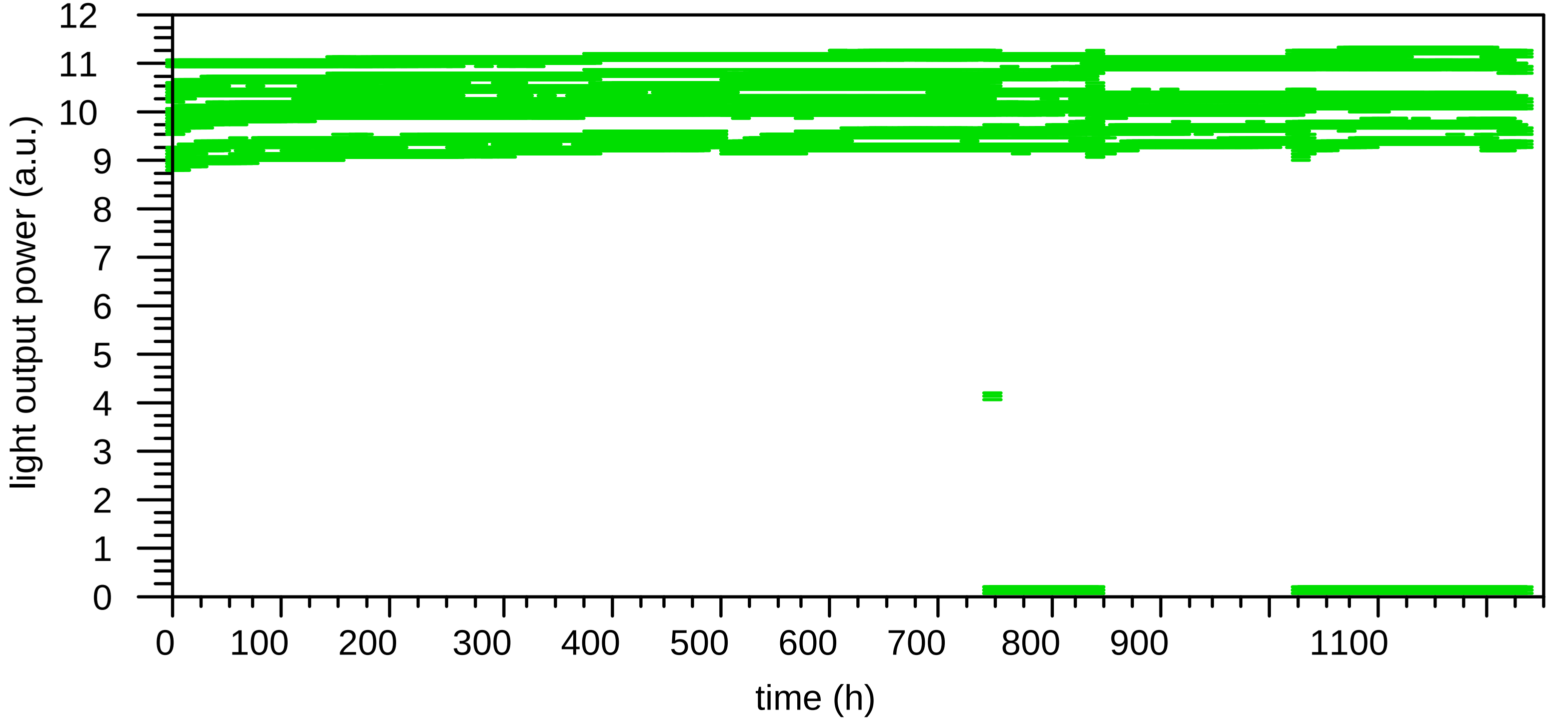
90 µm emission spot





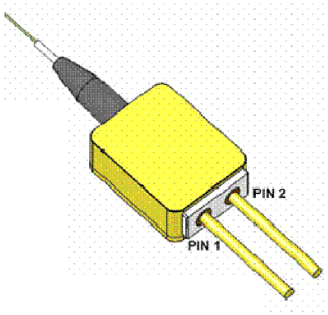
- Electro-Optical
  - Power: 8 W @ 8 A
  - Reliability: <5% fail in 10'000h

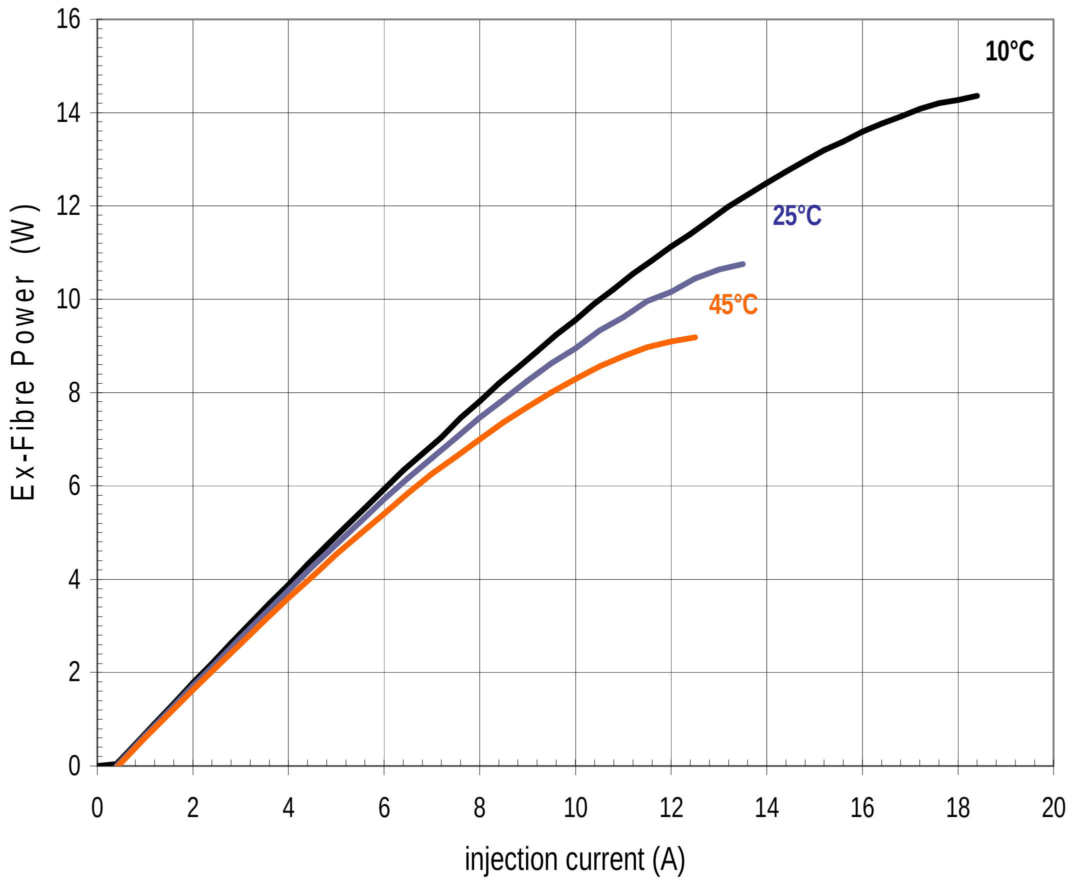
Broad Area 960nm (SES8-960-01)



- W=90um, P=13A (11W), Tj=130C
- Multi Cell Testing ongoing

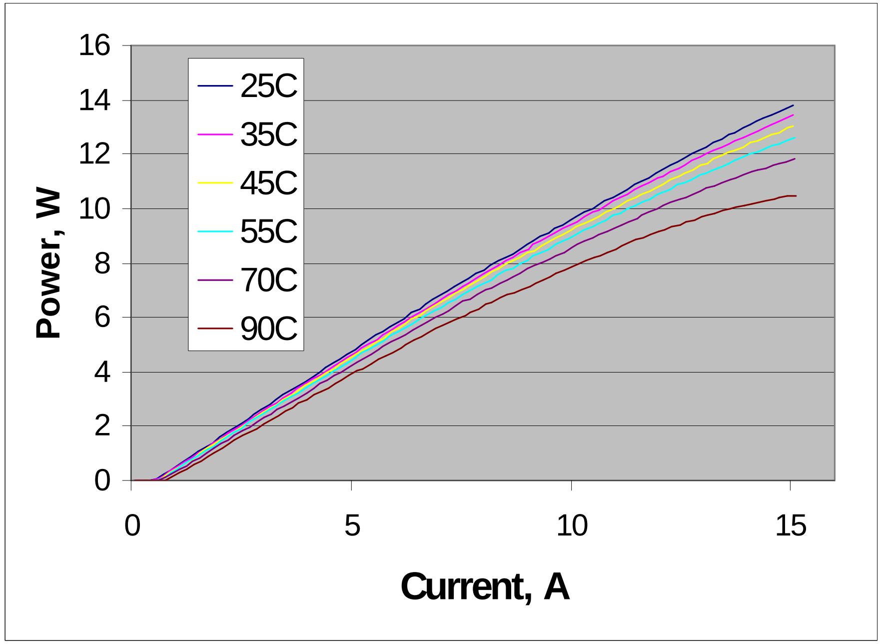
MM Uncooled Module with >14W

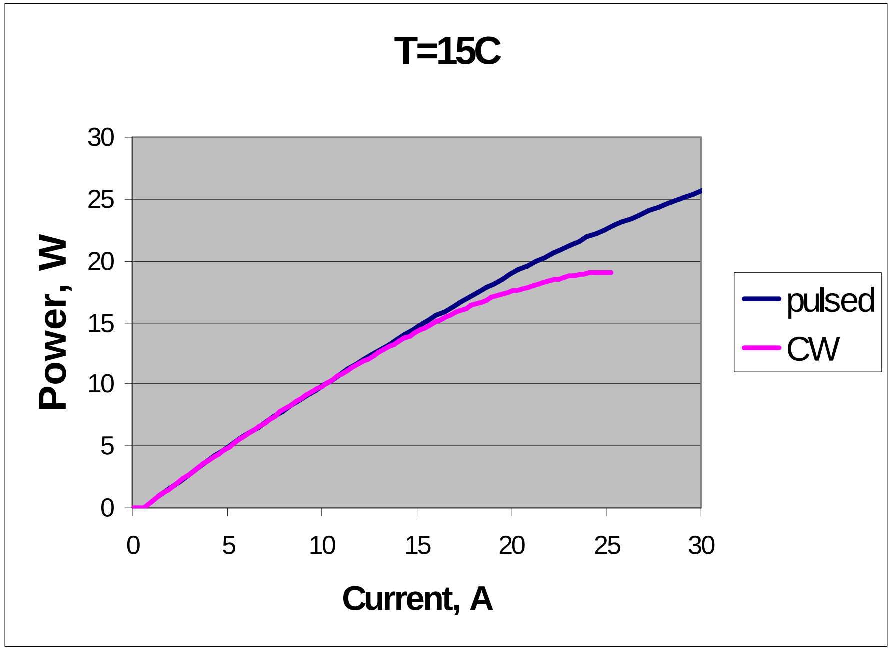




- Record Performance:
  - >14W @ 18A and 10°C T_{hs}
  - Standard MU package
- Module fully qualified
- MSA with EM4

New generation 9xx broad area chip





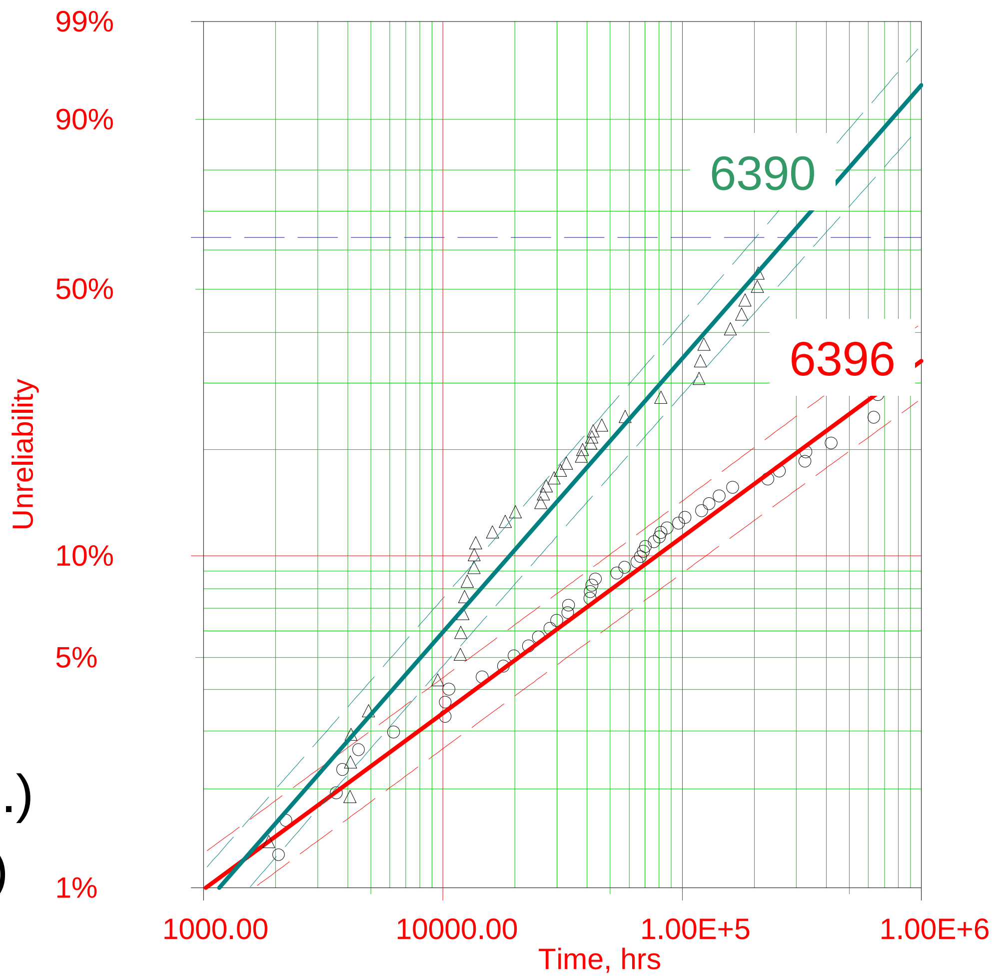
- 19.0W maximum CW power from ~ 100um aperture

6396 Chip Reliability Improvement

- MLE Results:

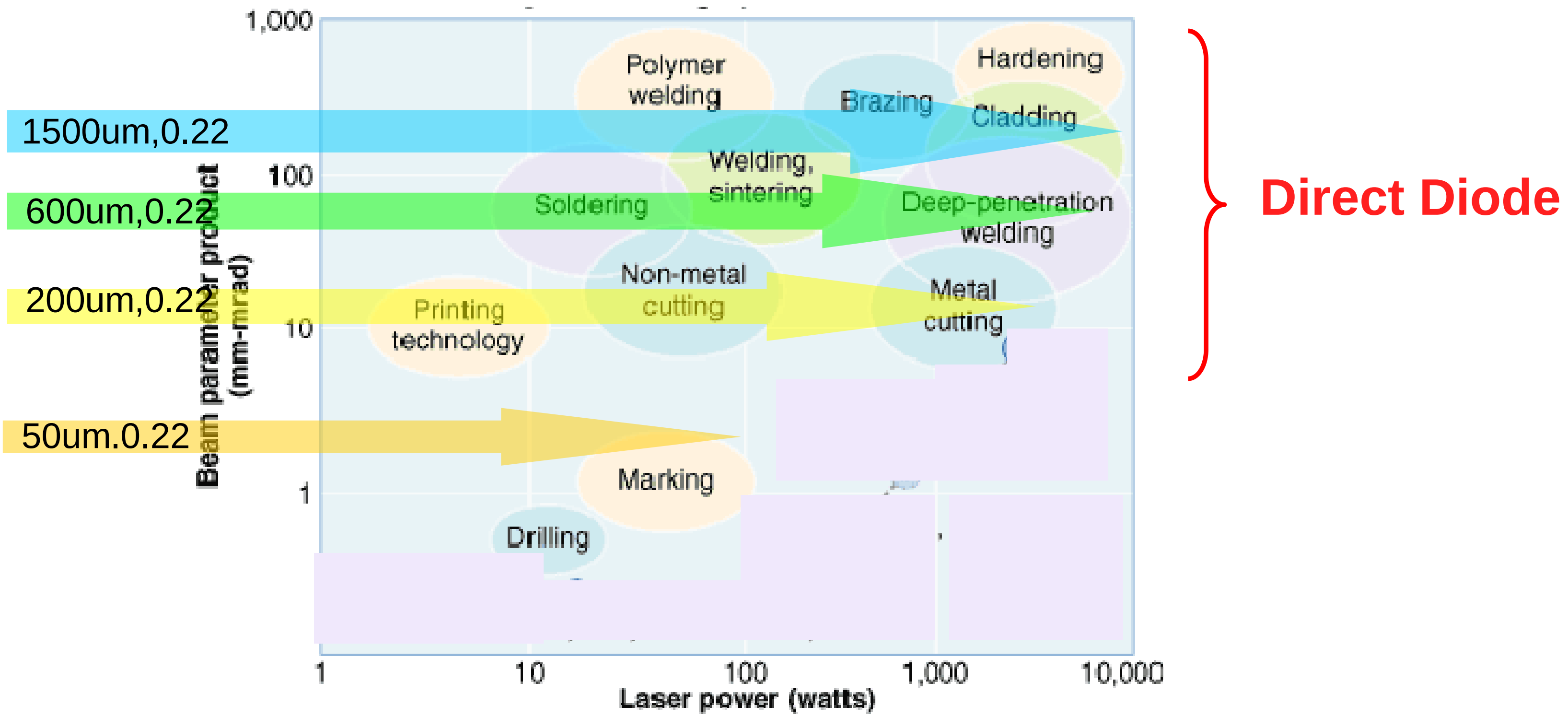
$$\beta \quad = 0.54$$
$$E_A = 0.61 eV$$
$$n \quad = 2.7$$
$$\eta_{op} \quad = 5.1 \cdot 10^6 \; hrs$$

- 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

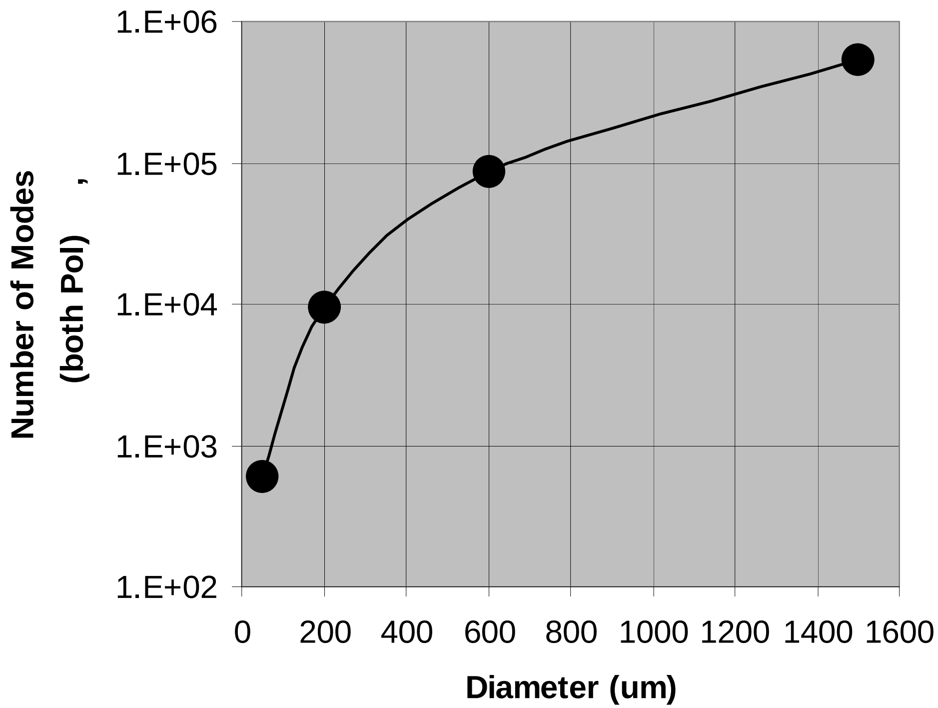
Power Photonics: Beam Machining Tool



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

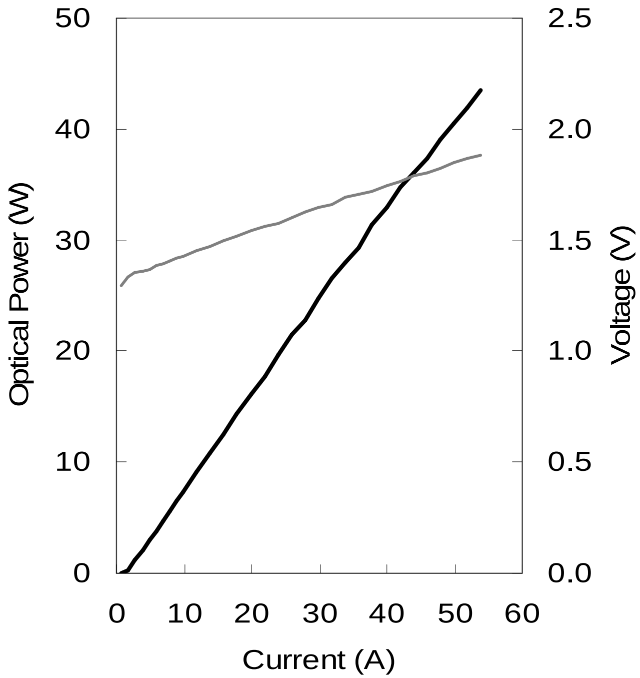
- Many applications do not need diffraction limited beam:
  - Direct Diode

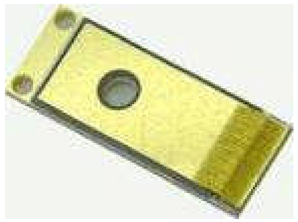
Number of Lateral Modes in Fiber



- With single mode lasers at 0.5W, all material processing needs can be met
- ‘Just’ challenge of coupling single mode laser diodes to fiber

Integrated Array of Single Mode Lasers





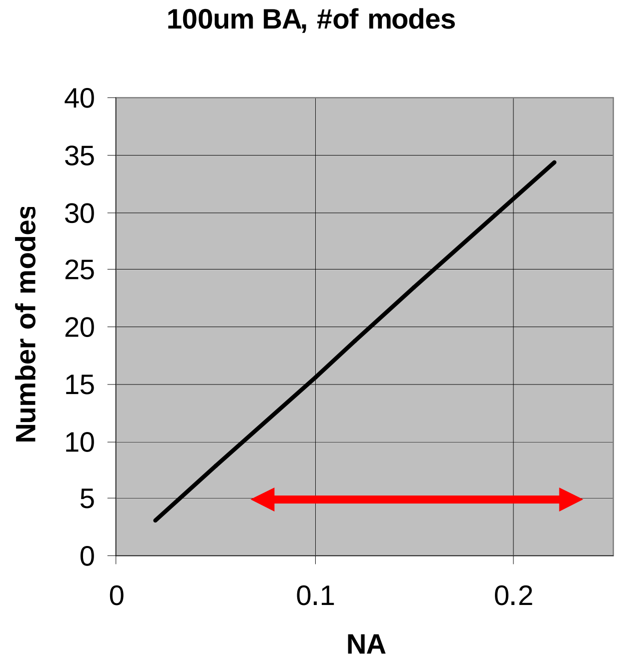
Single Mode Bar:

- 50 single mode lasers from 1 cm bar
- Power: 40W @ 50A
- Wavelength: 975nm

Product (by LIMO): Single mode laser bar coupled with lens array to 50um fiber:

25 W from 50um NA=0.22

Number of Lateral Modes in BA chip

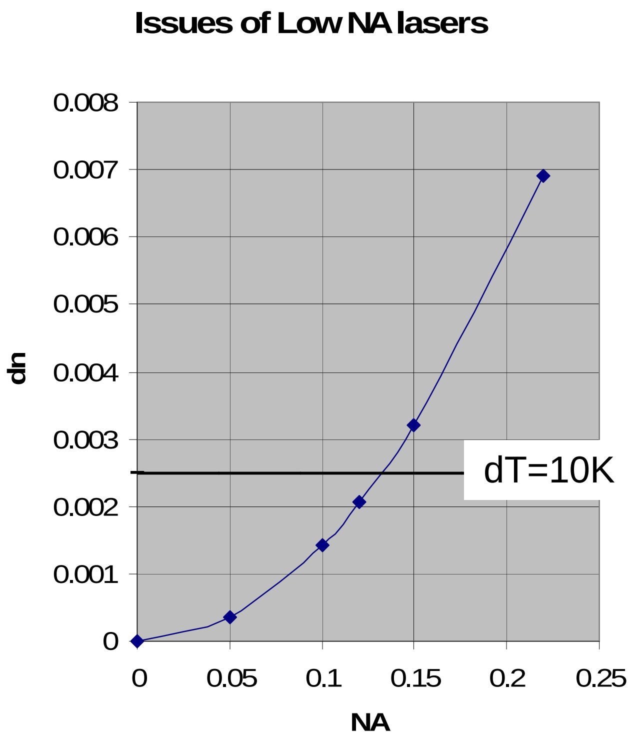


- Low NA broad area laser radiance:
  - Closing in on single mode lasers
  - 8W from NA=0.15NA: 400mW per lateral mode

- Reduce NA of broad area laser to increase radiance
  - NA dominated by thermal blooming
  - ->Need chip with very high power conversion

Low NA Broad Area Lasers: Thermal Blooming

Top view of BA laser



- Low NA laser
  - Achieved by low dn waveguide
- dn
  - Ridge
  - Parasitic through lateral temperature profile
    - dT=10K -> dn=0.0025 -> NA=0.13
    - Leads to ‚blooming'

Diode Power Conversion

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

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

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

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

Bandgap discontinuities
1. Thermal and vertical leakage
2. Injection barriers

Mobility:
Series resistance
Density of States:
Free carrier absorption

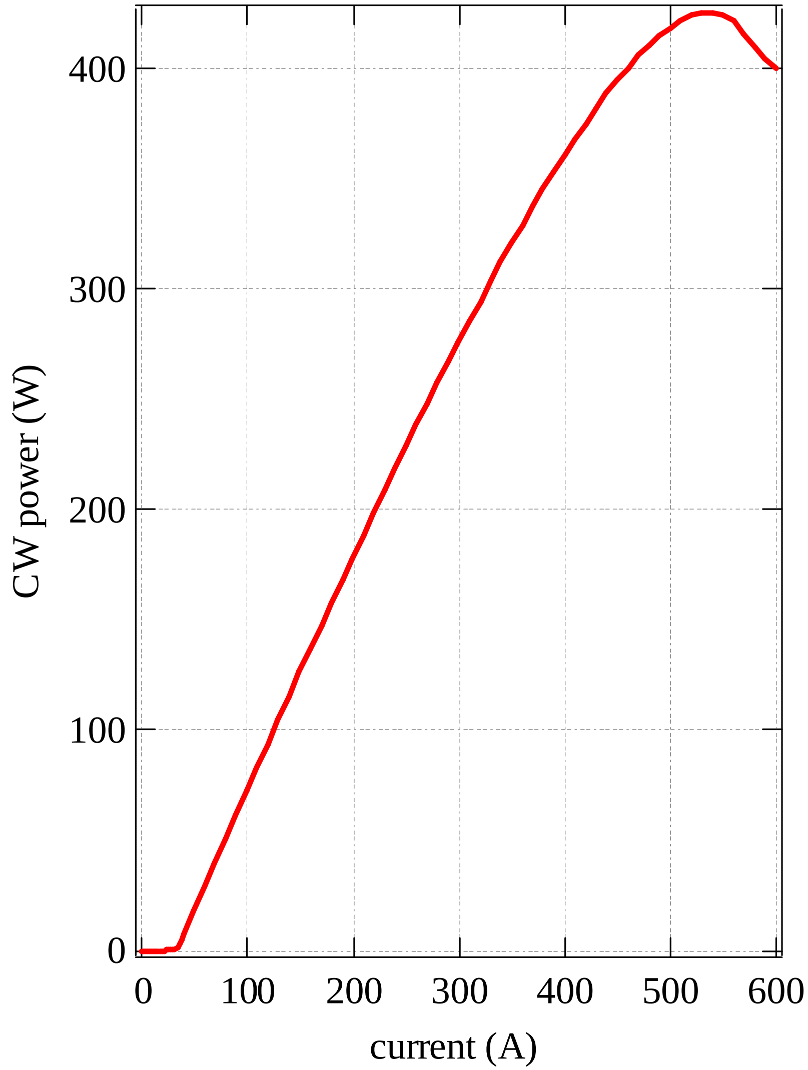
Material limits: Even after optimized mirror losses (S_f , R_f , R_b) and low threshold current.

- 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:

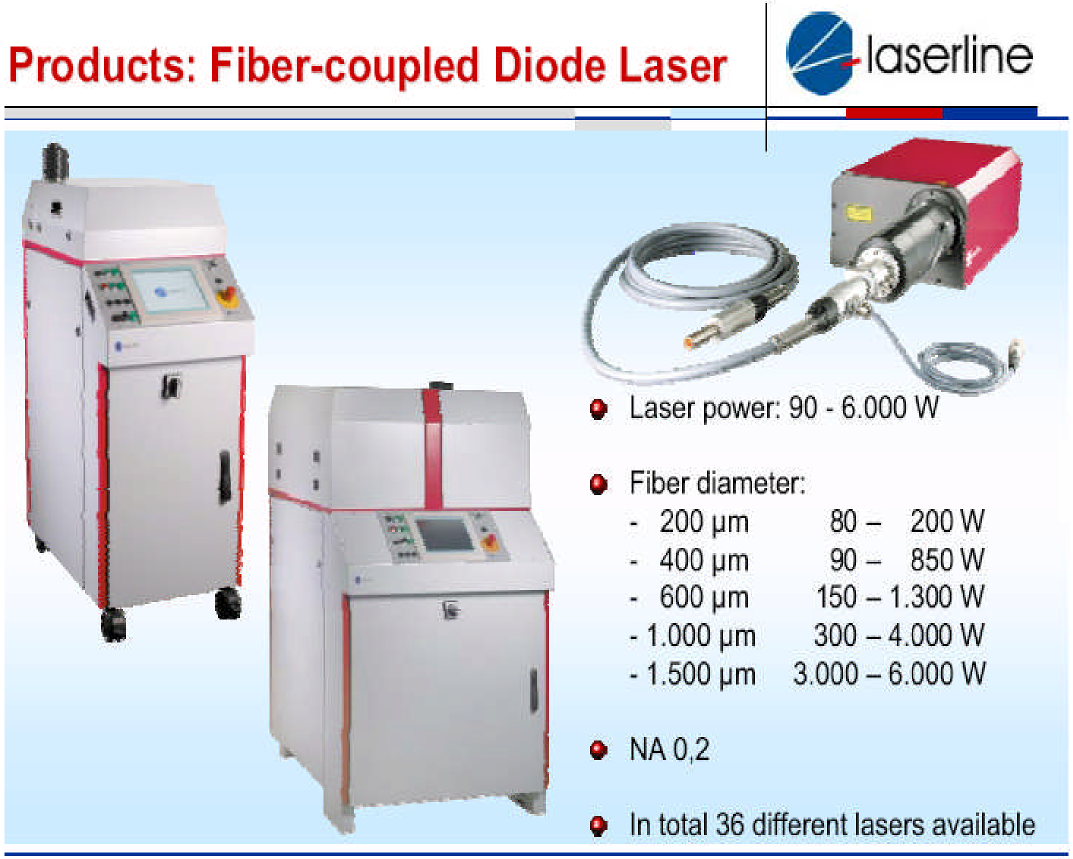
- InGaAlAs material system
- Asymmetric (thin p-region), low aluminum, low confinement LOC, low doping levels
  - Holes have poor conductivity and high free carrier losses.
- Relatively low barriers for high mobility and good injection (some thermal and vertical leakage)

Bar with 425W CW at 980nm



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

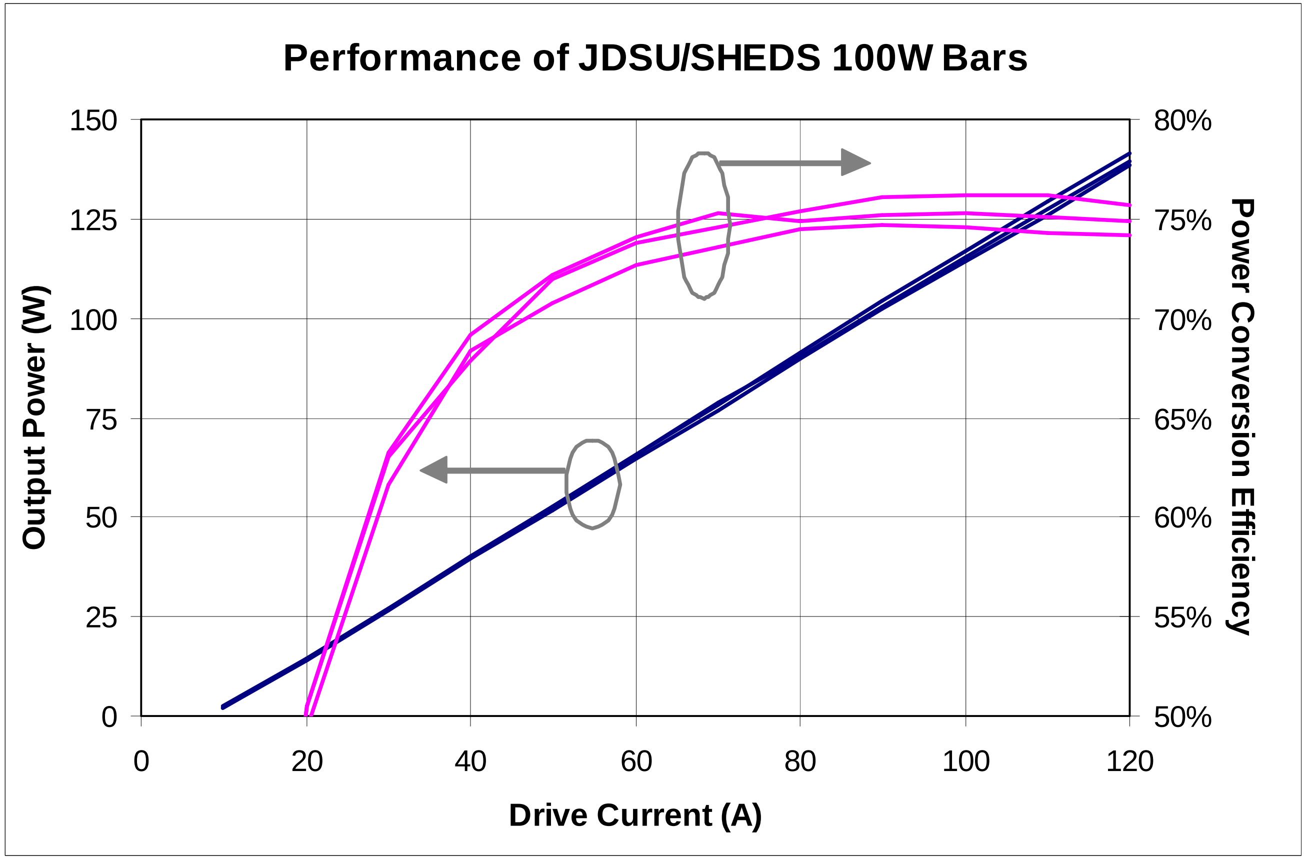
Direct Coupled Diodes:



Laserline GmbH, Germany

- Practical limits to radiance?

High-efficiency bars



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

High Power Laser Diodes

Single Mode Pump Diodes: Matured

- Frequency doubling for displays, Printerarrays, Seed lasers (Fiber Lasers)

Broad Area Pump Diodes:

- Fiber Lasers
- Direct Diode Systems

Power Photonics still at beginning. Enabled by laser diodes with

- Power efficiency
- Beam matched to fiber coupling