High-Power Pump Diode Lasers

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High-Power Pump Diode Lasers

1. **High Power Pump Diodes Lasers**
   - History
   - 1480nm vs 980nm

2. **980nm Single Mode Pump Diodes**
   - 980nm Chip
   - Packaging
   - State of the art

3. **9xxnm Multi Mode Pump Diodes**
   - Fiber Lasers
   - State of the art

4. **Outlook**
   - 980nm for Telecom: Mature
   - Pump Diode: Fiber Lasers
   - Pump Diode: Direct beam

Acknowledgement
- Mark Ives, Bookham
- Dr. Norbert Lichtenstein, Bookham
- Dr. Toby Strite, JDSU
- Dr. Erik Zucker, JDSU

History
EDFA: Demonstrated 20 years ago

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

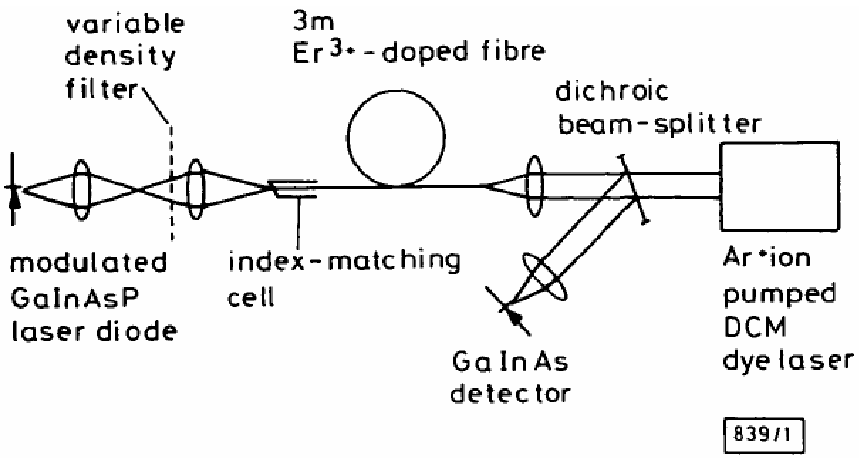

Fig. 1 *Experimental configuration for fibre amplifier*

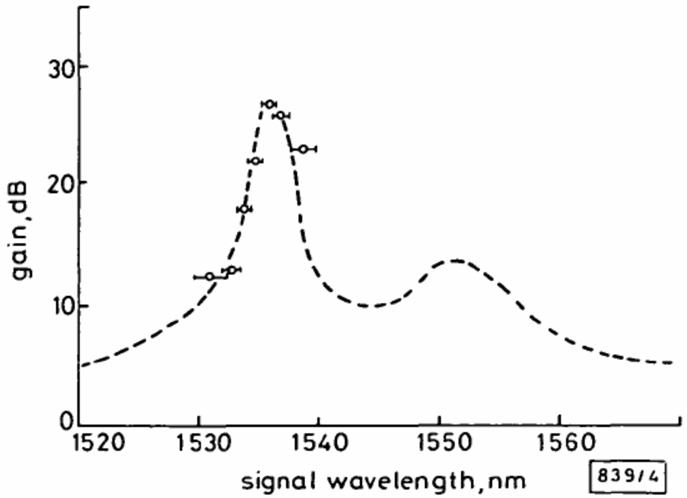

Fig. 4 *Gain spectrum and spontaneous emission*

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

- *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*

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3rd August 1987

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

History:
Pump Diodes: OFC88 and ECOC88

1. E. Snitzer, H. Po, F. Hakimi, R. Tumminelli and B.C. McCollum: "Erbium fibre laser amplifier at 1.55μm with pump at 1.49μm and Yb sensitised Er oscillator", OFC '88, New Orleans, paper PD2.

2. RARE-EARTH-DOPED FIBRE LASERS AND AMPLIFIERS

D.N. PAYNE AND L. REEKIE
OPTICAL FIBRE GROUP, THE UNIVERSITY, SOUTHAMPTON, S09 5NH, U.K.

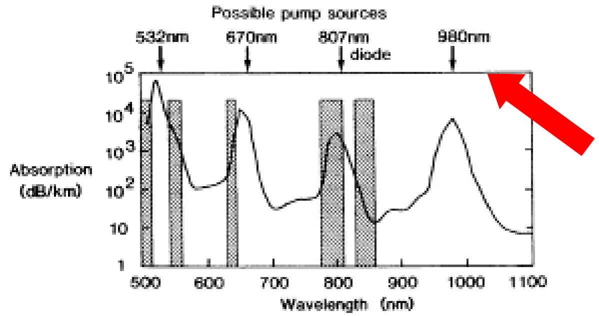


Fig. 1 Absorption spectrum of Er^{3+} in a fibre co-doped with Al_2O_3. Shaded areas are regions of excited-state absorption. Possible pump-source wavelengths are also marked.

- 980nm and 1480nm pump diode lasers among other wavelengths (532nm, 670nm, 807nm)
- Early on: Choice of
  - 1480nm: Early availability and high power
  - 980nm: Low noise but low pump power (pump diode reliability!)

1480nm vs 980nm

Figure of Merit	1480nm SM EDFA	14xxnm (MM) Raman	980nm SM EDFA	940nm MM YEDFA	Comments
Noise	Poor	**Excellent (remote)**	Good	Good (NB)	
Max Power Output	Good	Good	Good	**Excellent**	
Wallplug conversion efficiency	2%..3%	1%	**5%.. 15% (uncooled)**	10%..15%	Amplifier Watt out/ Total power in
Gain flatness	Good	OK	Good	Narrow band	
Bandwidth	Wide (C+L)	Good	Wide (C+L)	Narrow	
Reliability	Excellent	Good	Excellent	Good	
Max Temperature	T<70C	T<70C	T<75C	T<45C	
Packaging	Isolator, lenses	Direct fiber/FBG	Direct Fiber/FBG	Direct Fiber	Cost
System embedding	Easy	Complex	Easy	Easy	
Application	Legacy Booster	remote preamp (FEC!)	DWDM Preamp DWDM Booster	Narrow band CATV Booster	

Pump Diodes of Choice:

- Telecom:
  - Cooled and uncooled 980nm: Low Noise, high output power, high efficiency
- CATV:
  - Uncooled 940nm: High Output Power, high efficiency

- Telecom remote preamp:
  - 14xx Raman
- Legacy Booster, Legacy L-band, remote preamp:
  - 1480nm Pump

980nm Single Mode Pump Diodes

8xx and 9xxnm Single Mode Pump Diode: 20 years ago

- Investigate COMD in 80's for InGaAlAs lasers for
  - Nonlinear optics, i.e. 980nm frequency doubling in KTP in 1987 for MO storage)
  - Free space communication
- Narrow stripe laser:
  - Mirror blows up at high powers (COMD)

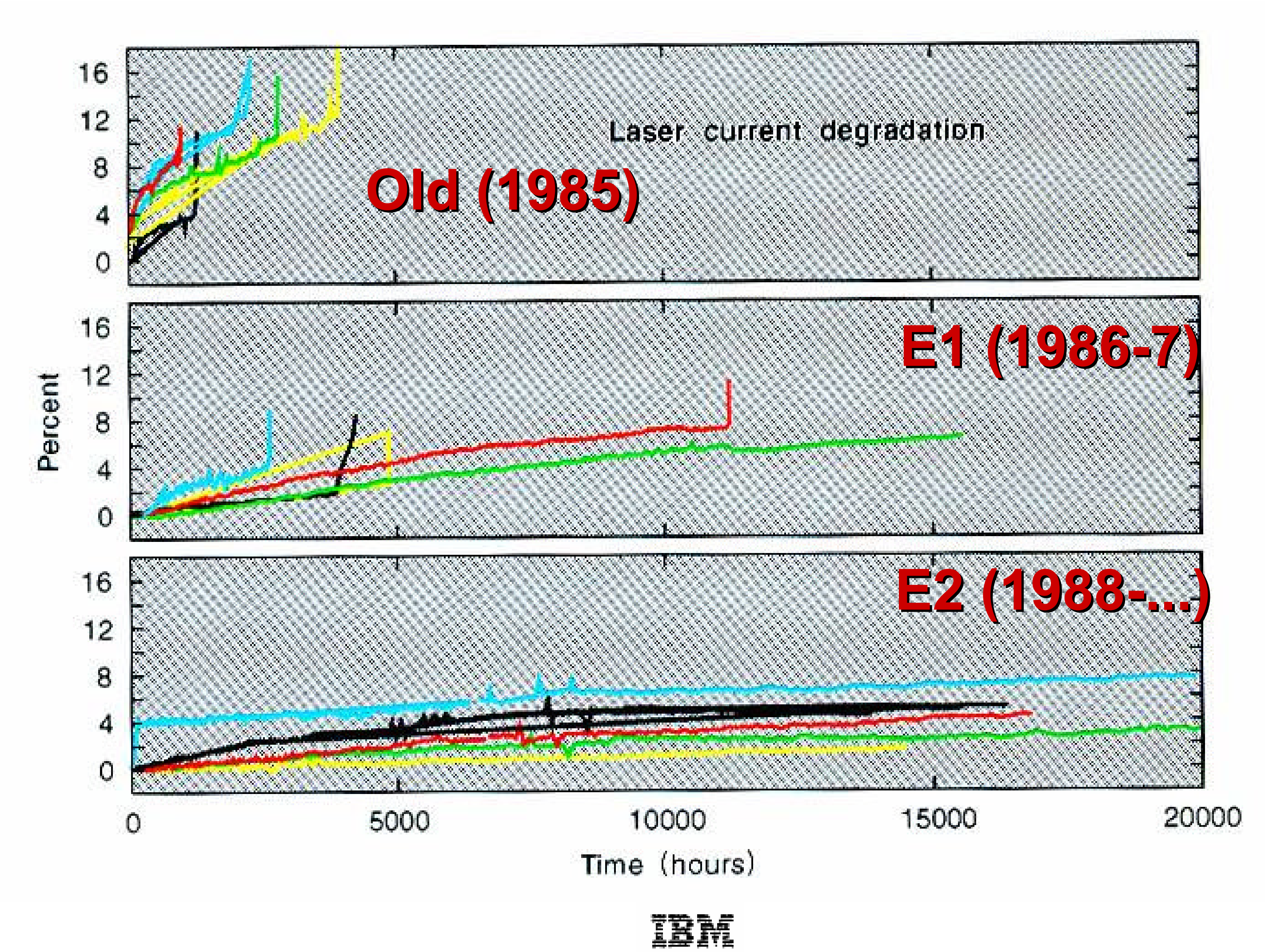
-> Spread beam to decrease power density at facet:

- Coherent arrays
- Surface grating lasers
- MOPA
- Taper Laser
- Alpha DFB
- VCSEL

Beamquality degrades. Does not meet telecom requirements

Poor power conversion efficiency

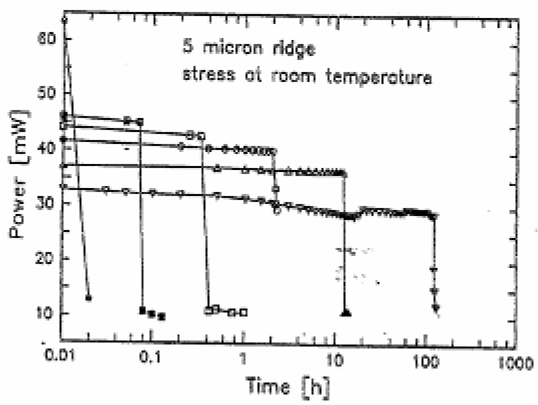
Single Mode Pump Diode: Facet passivation at 830nm and 980nm



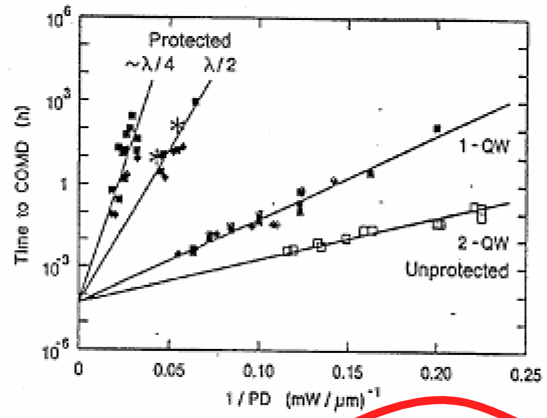
980nm Single Mode Pump Diode: Time to COMD

Mirror Passivation

Time to COMD



Arrhenius Plot



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

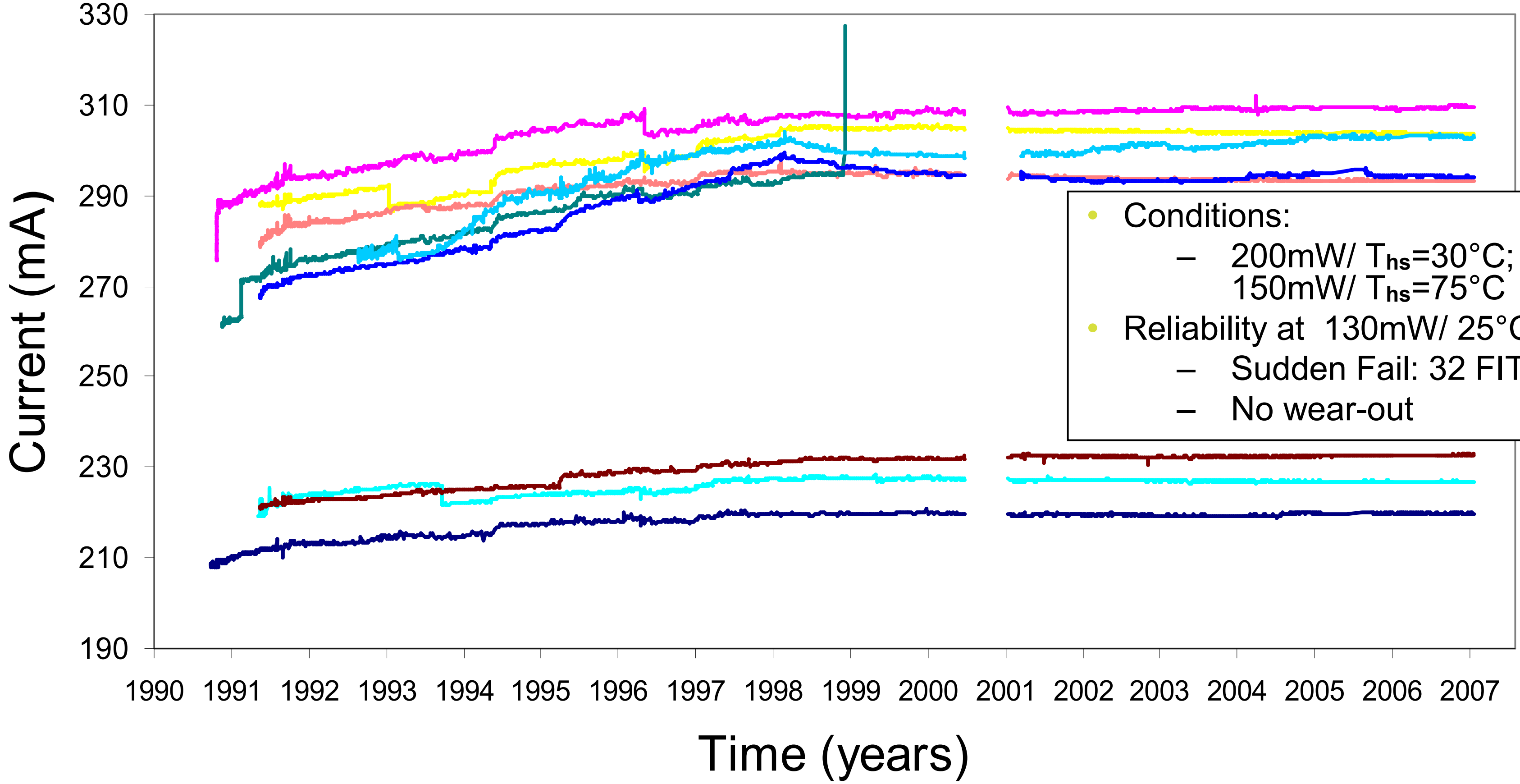
$$T_M = c \times \text{Power density}$$

Chemist fixed problem

Solved in 1987 (E2)

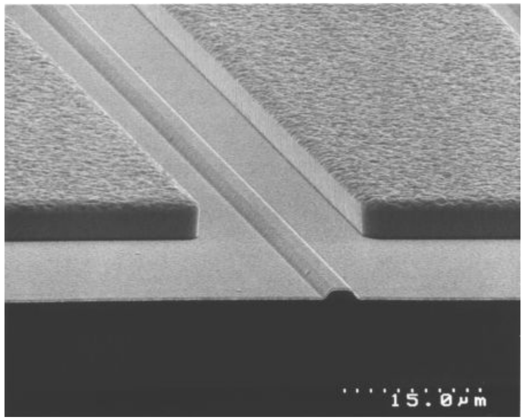
OSA_91 IBM 11/91 (Ch. Harder)

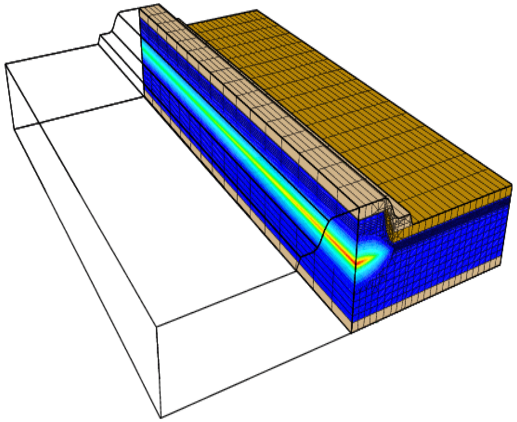
980nm Methuselah Lasers: 17 Years of Stress Test

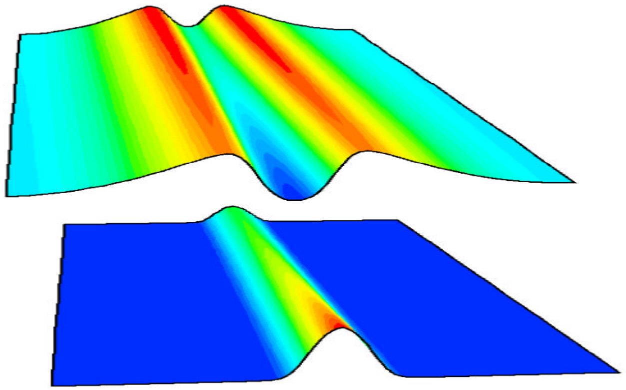


- Conditions:
  - 200mW/ T_{hs}=30°C; 150mW/ T_{hs}=75°C
- Reliability at 130mW/ 25°C:
  - Sudden Fail: 32 FIT
  - No wear-out

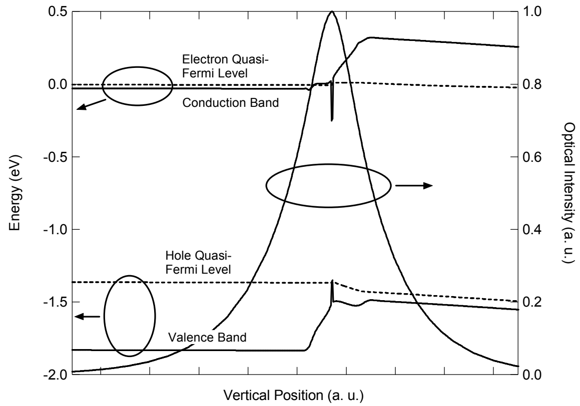
980nm Single Mode Pump Diode: Ridge Waveguide



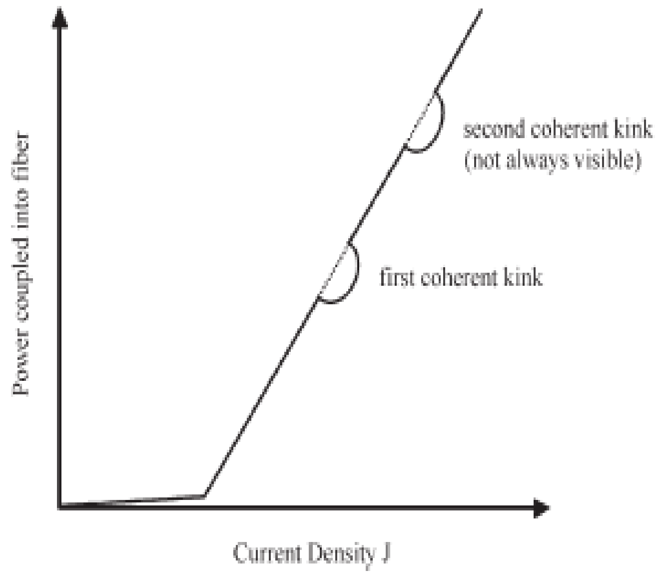


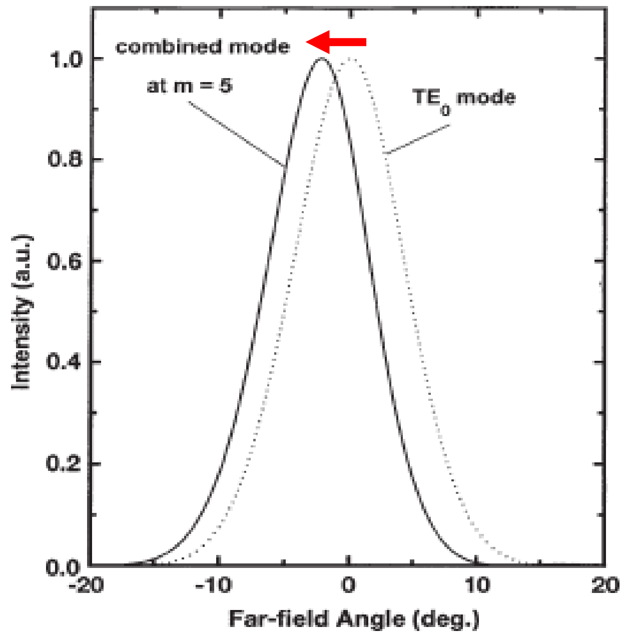


- Ridge Waveguide
  - One growth step, simple process
    - Built in reliability
    - InGaAlAs for best material properties
  - Confinement
    - Index guided mode: High linear power and excellent coupling to fiber
    - Temperature insensitive current confinement
  - Scalability
    - Increase power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



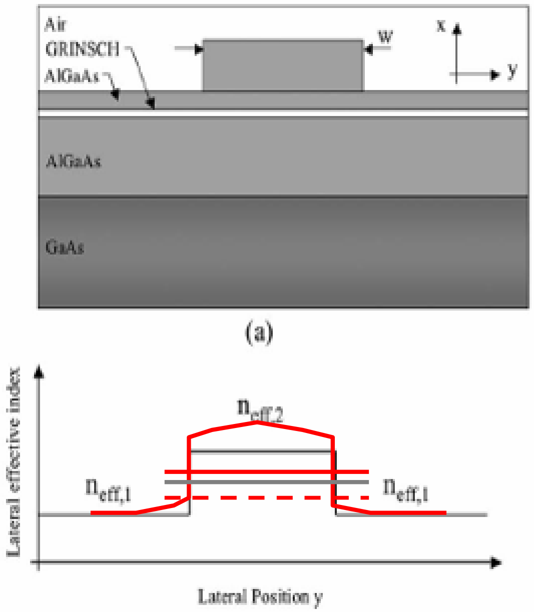
980nm Single Mode Pump Diode: ‘Shift’ Kink: Observation



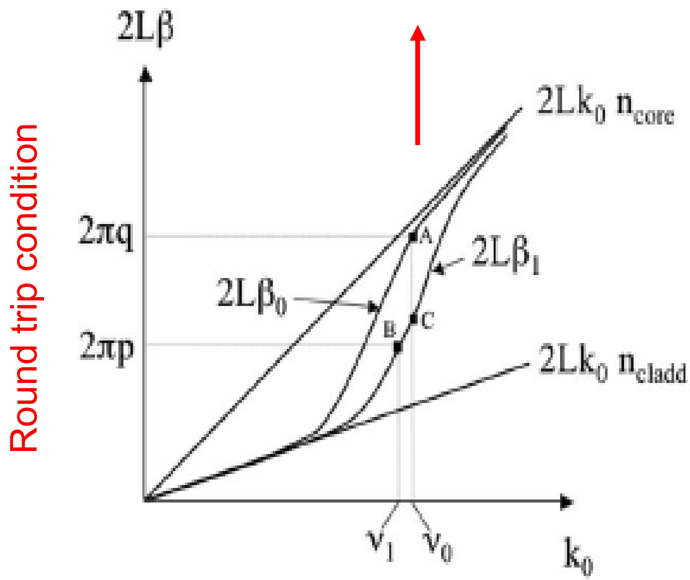


- Observation (1991)
  - Sudden kinks in fiber coupled power
- Farfield observation
  - Still single ‘humped’, but shifted during kink. Still single mode? (no!)
- Standard countermeasure:
  - Increasing loss for higher order modes (to keep them below threshold): Does not work

980nm Single Mode Pump Diode: Shift Kink: Lateral Mode Locking



Index moving up with temperatureprofile (drive current)

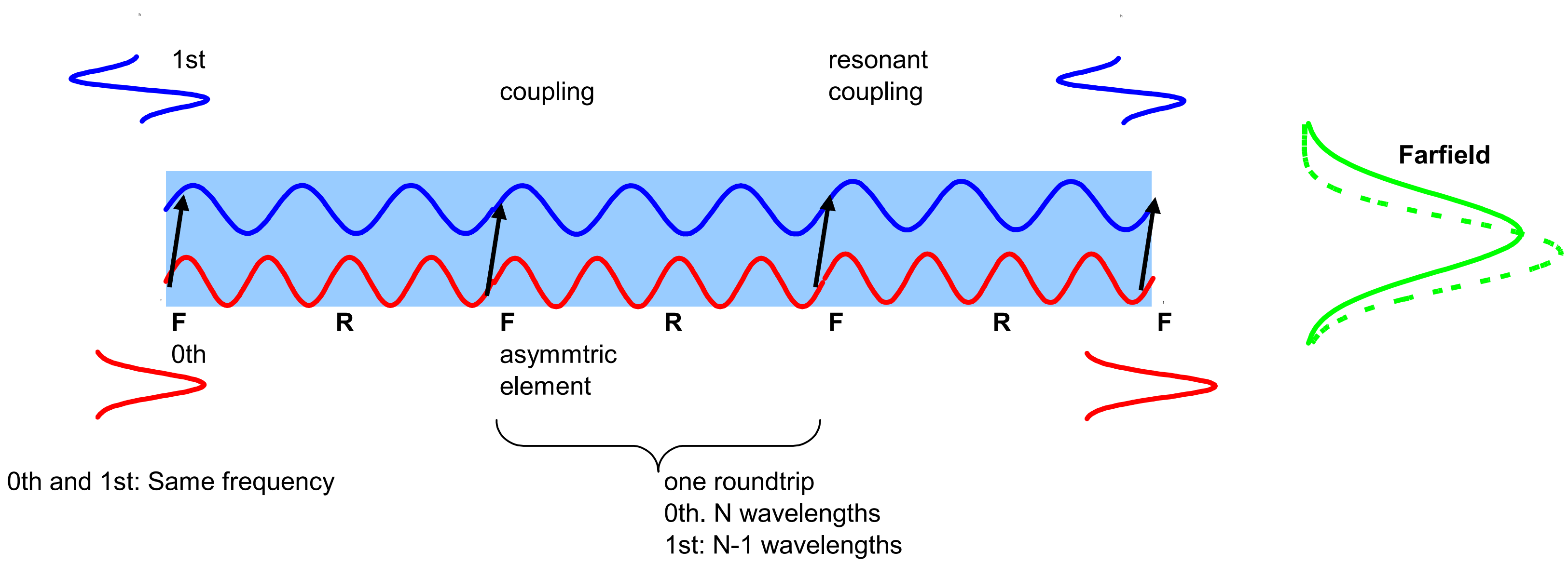


For $\upsilon_1 = \upsilon_0$

Coherent coupling

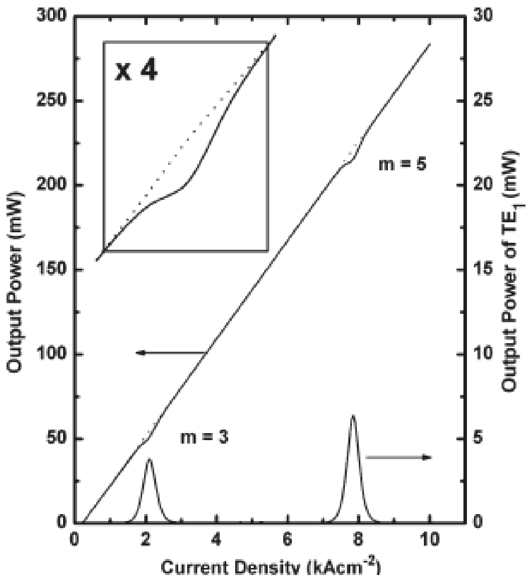
- Waveguide
  - Index increases with local heating
  - Waveguide becomes multimode
- Dispersion characteristics of waveguide
  - Phase lasing condition (integer number of wavelengths in one roundtrip) can be meet for one frequency ($\upsilon_0 = \upsilon_1$) for fundamental and higher order modes at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

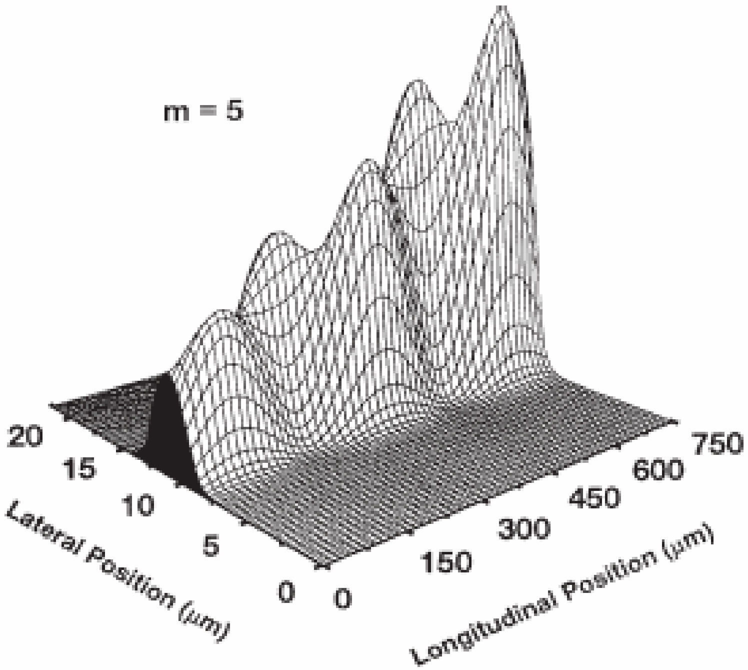
980nm Single Mode Pump Diode: Shift Kink: Coherent Coupling



- 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

980nm Single Mode Pump Diode: Shift Kink: Lateral Mode Locking



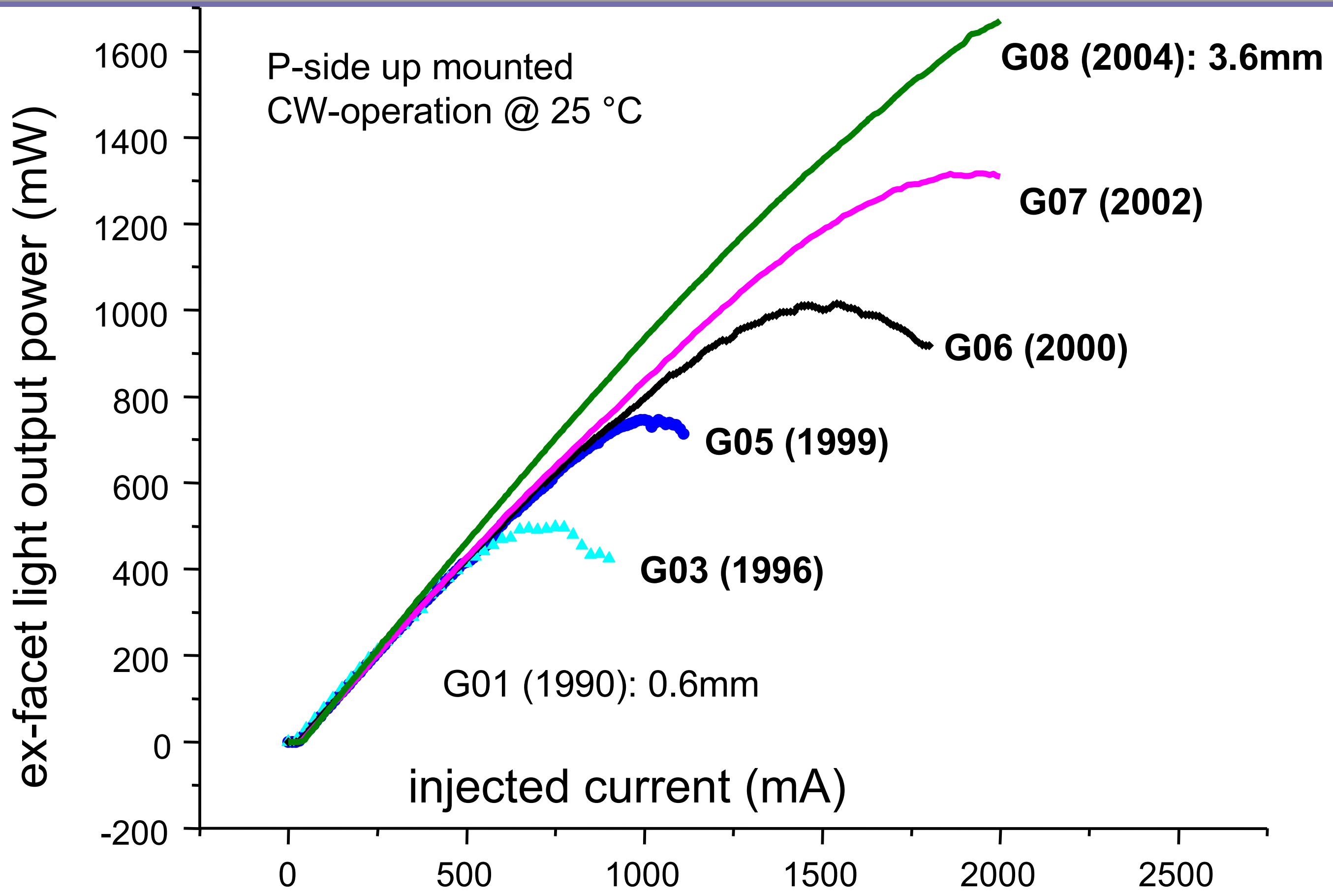


Coherent Supermode:

- Introduction of loss for higher order modes just reduces overall efficiency
- Interference within waveguide

Achtenhagen, Hardy and Harder, JQE Vol24 pp2225

980nm Single Mode Pump Diode: Length Scaling

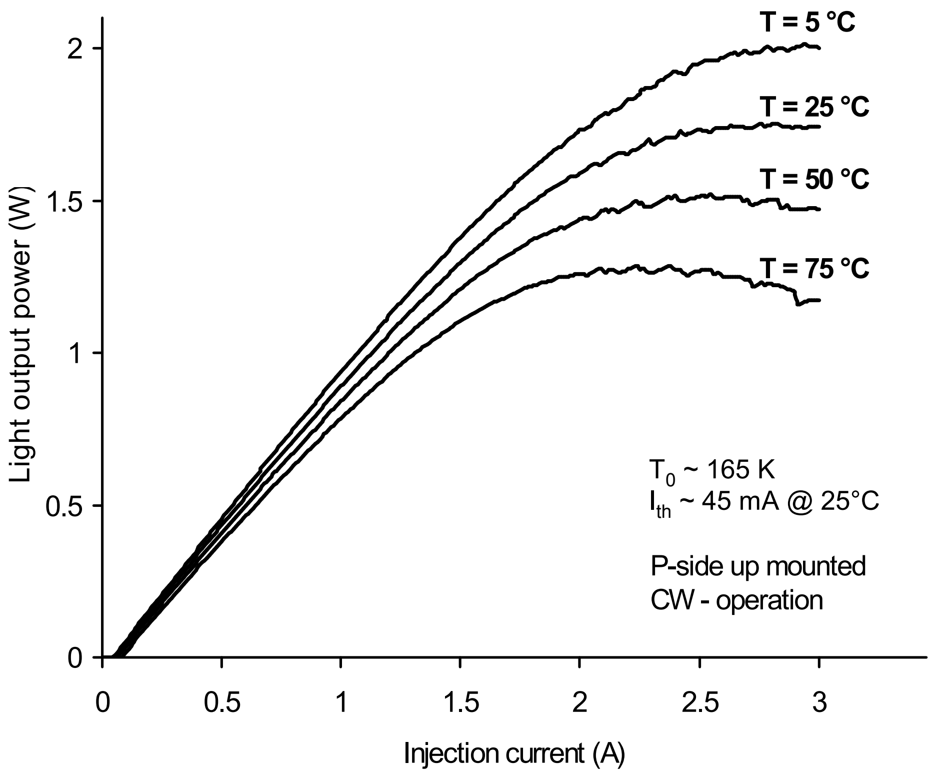


Improve performance by making laser chip longer

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

Courtesy Bookham

980nm single mode pump chip: 2004

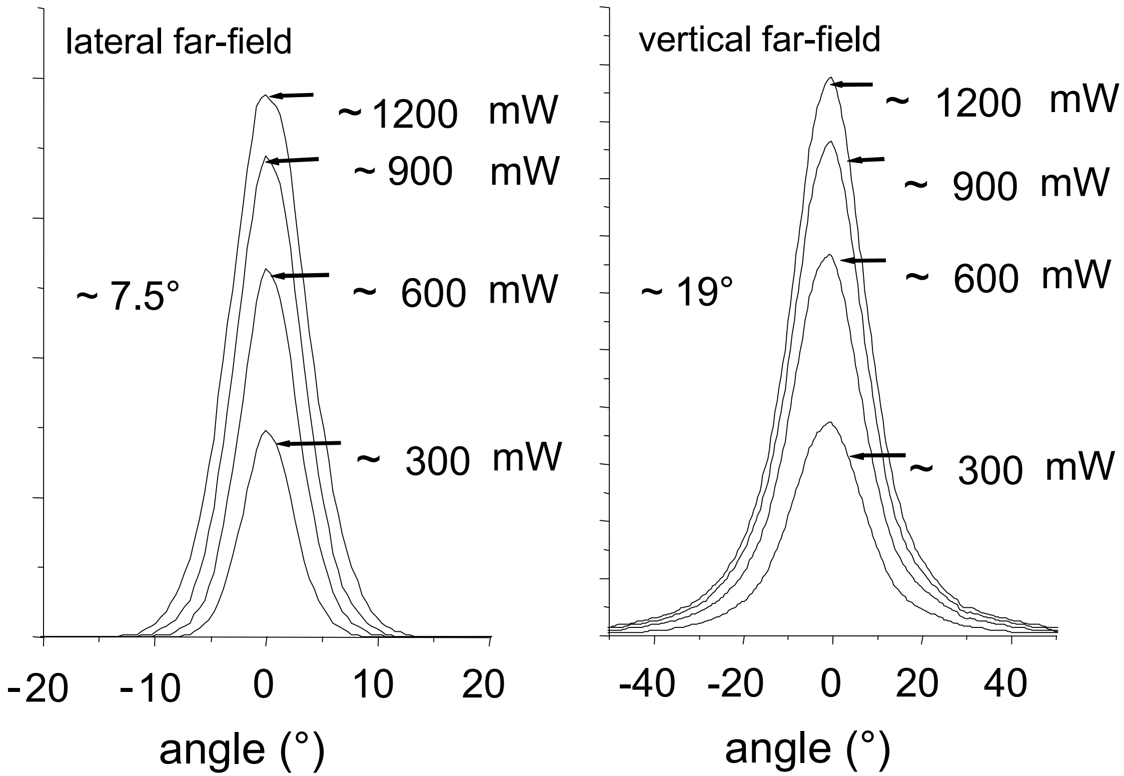


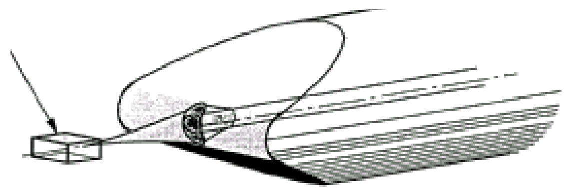
150MW/cm2

- 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

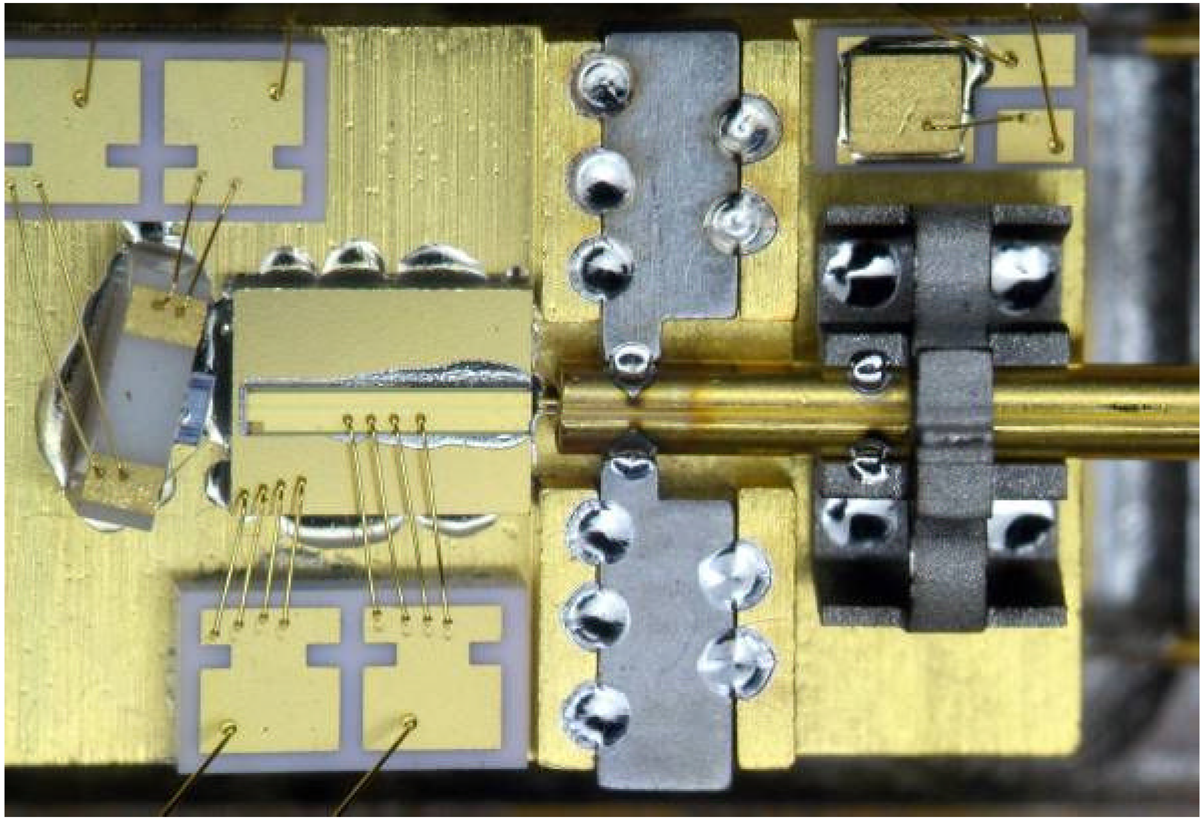
Single Mode Pump Diode: Beam match for fiber lens

CW operation
T = 25 °C



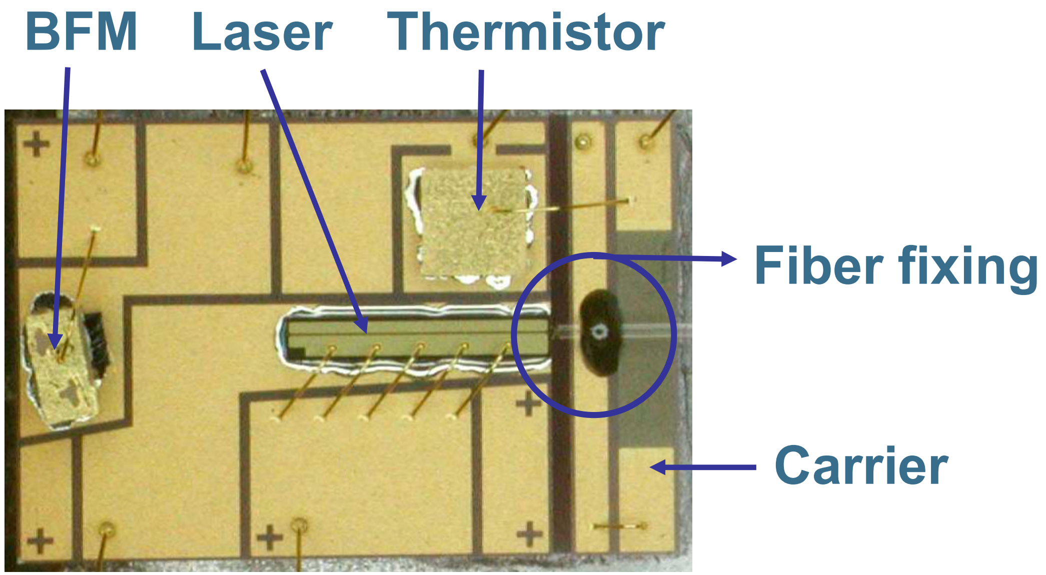


980nm Single Mode Pump Diode First Generation Package

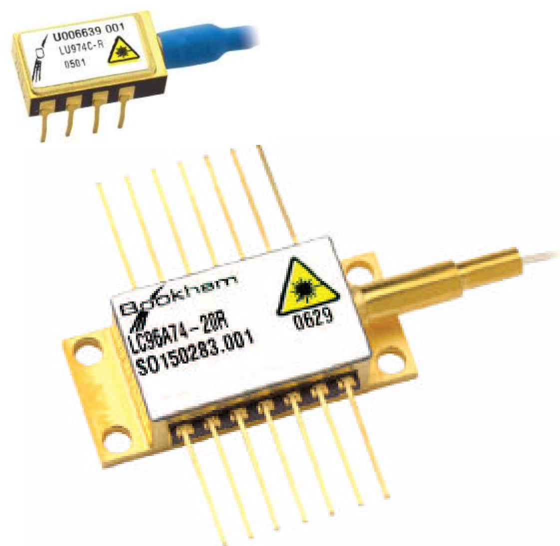


- Fiber fixing through spot welding
  - Kovar platform (for laser welding), poor thermal performance
  - Labour intensive
  - Post weld shift, Mechanical re-bend, creep during lifetime

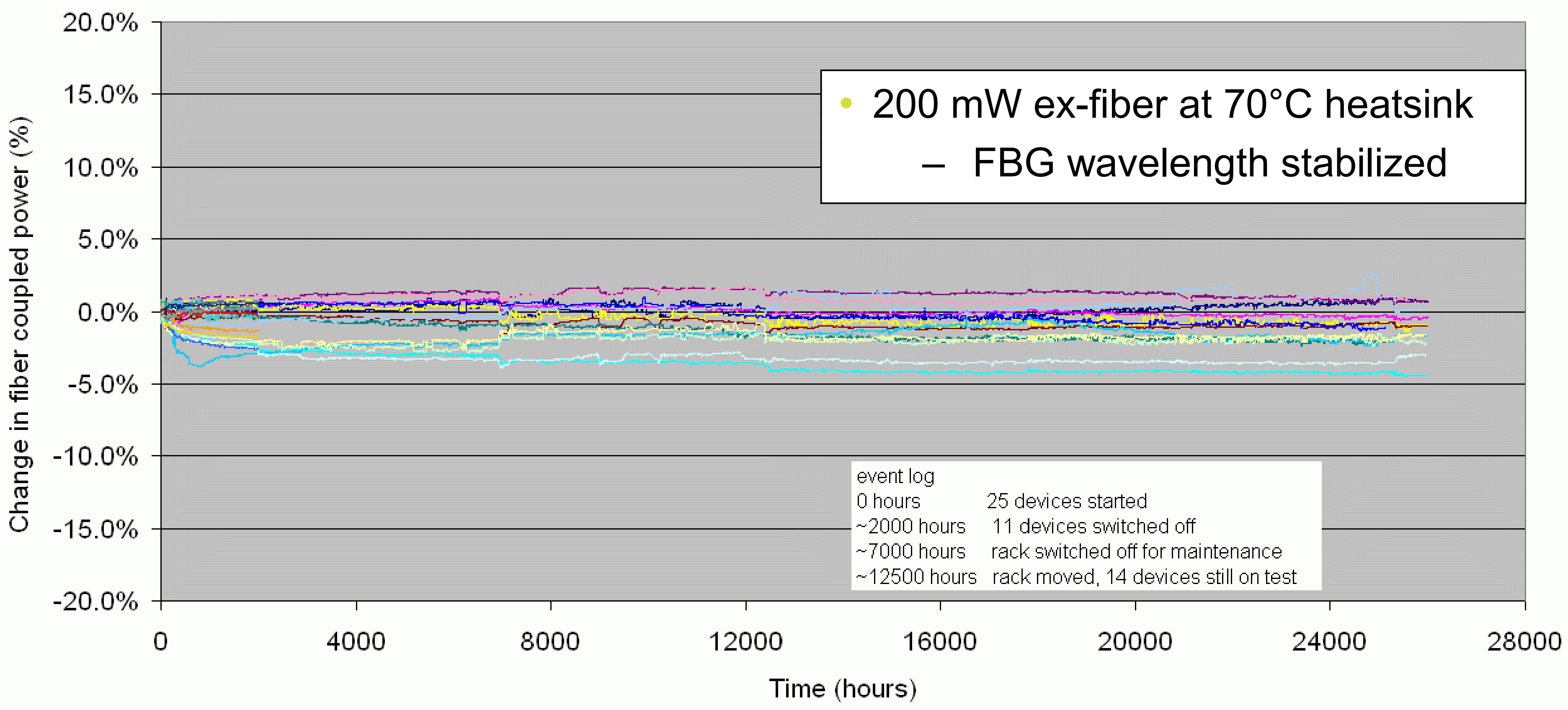
Planar Pump Module



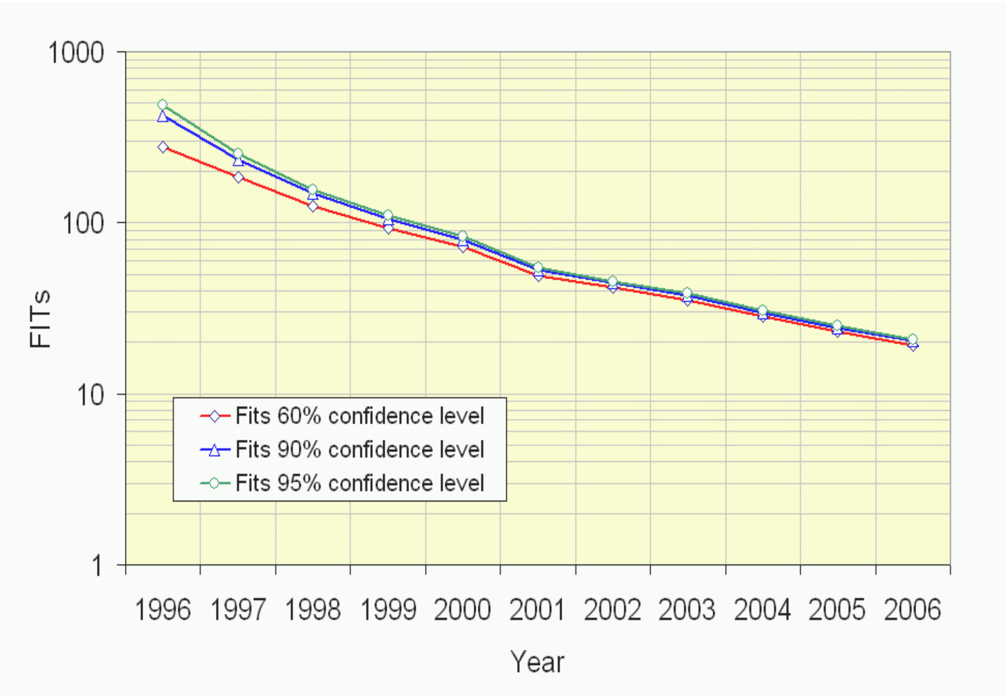
- Fully monolithic planar AlN substrate
  - Extremely low mechanical creep
  - Cost effective automation
  - Excellent thermal properties
- Used in Butterfly packages and coolerless MiniDIL
  - i.e. 400 mW Submarine MiniDIL, 600mW Butterfly



3 Years 980 nm MiniDIL Operation



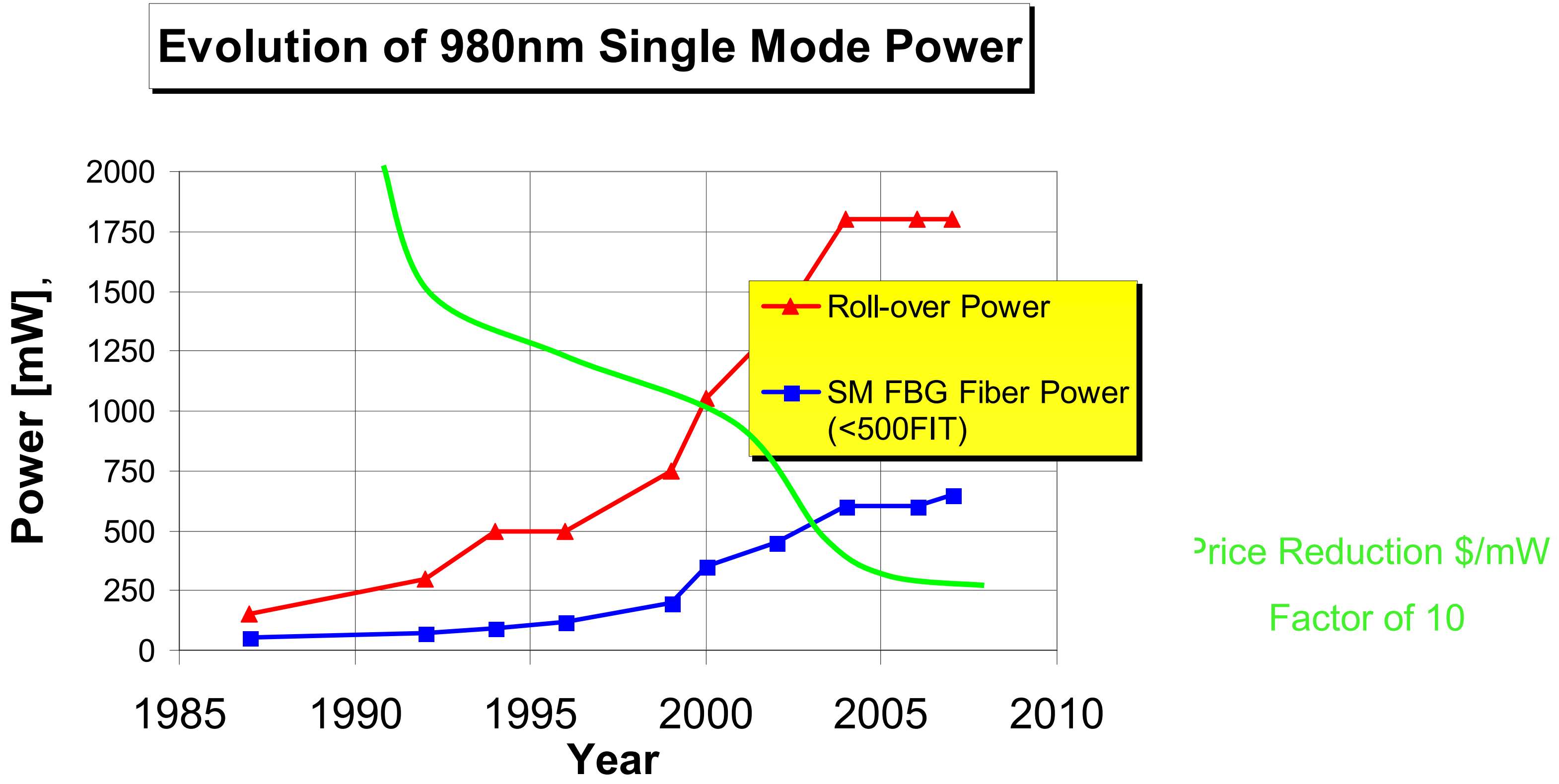
980 nm pump module failure rate track record



- By 2006:
  - 400’000 devices tracked
  - 16 billion device hours accumulated
  - 19FIT (roughly 300 field returns)

- Field return rate: Improving steadily year by year
  - All devices: Same basic “Bookham” technology
  - Pump power increased over the years

980nm Single Mode Pump Diode: Evolution

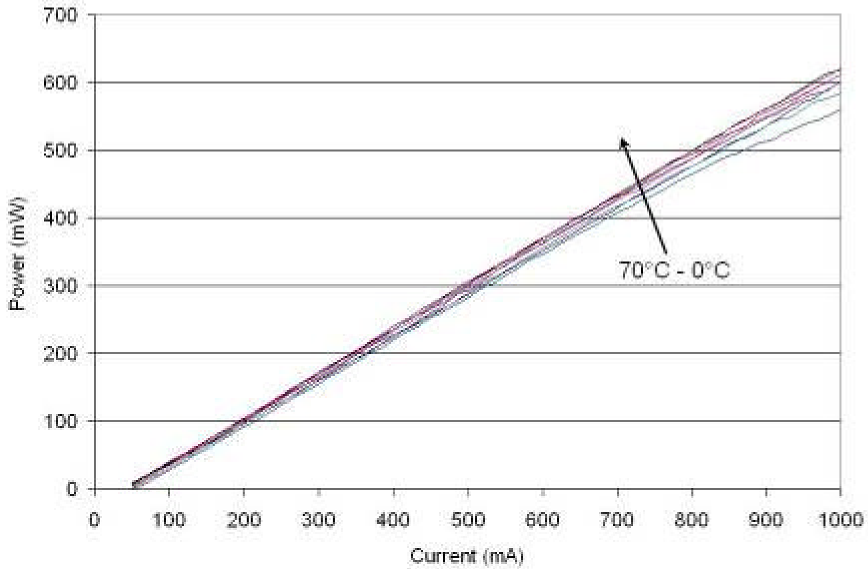


980nm Pump Diode Lasers: Matured

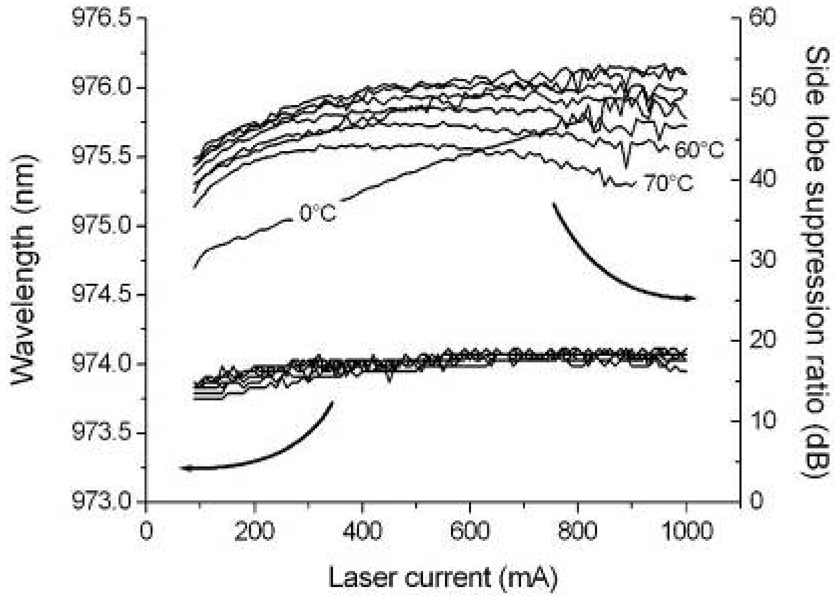
-> Power has reached plateau at 600mW .. 650mW
-> Cost reduction done: Assembly in China, One platfrom for various devices
-> Spectral stability and noise: Done
-> High efficiency: Done (Uncooled MiniDIL)

Submarine type MiniDIL
Performance from 0 °C to 70 °C

- 600 mW Power at 1 A operating current

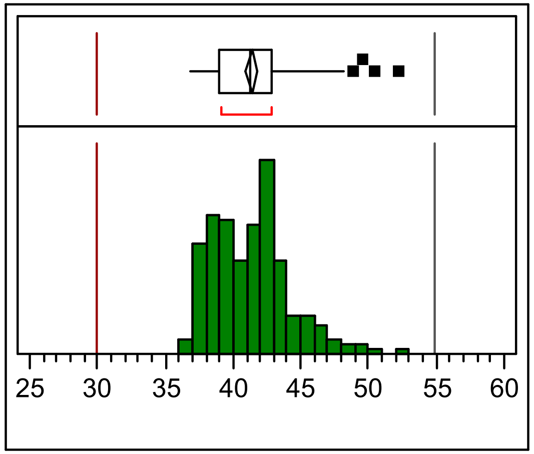


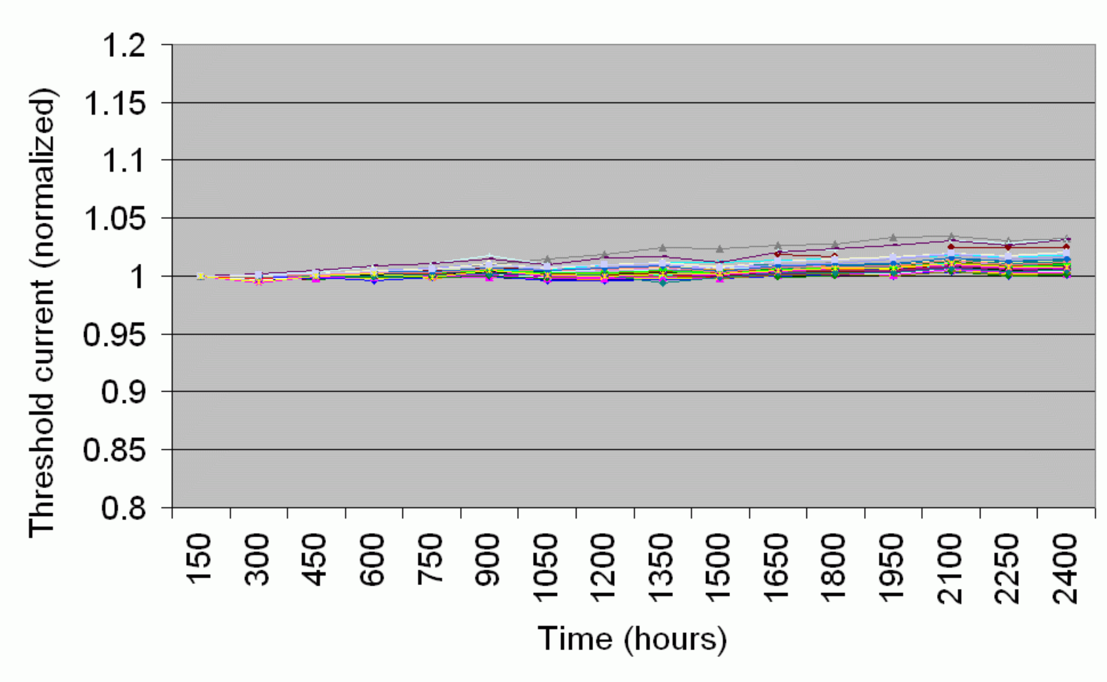
- Wavelength locked by FBG over 70 K with high side lobe suppression ratio



G08 lifetest: No significant change in threshold current

More than 100 devices at
1030 mA (850mW) / Tj=90°C



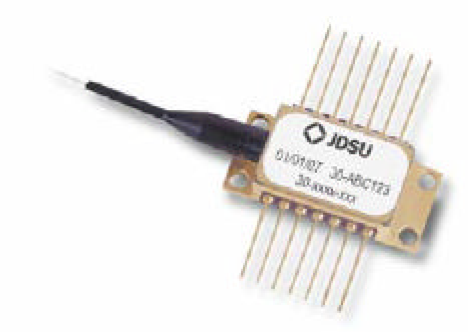


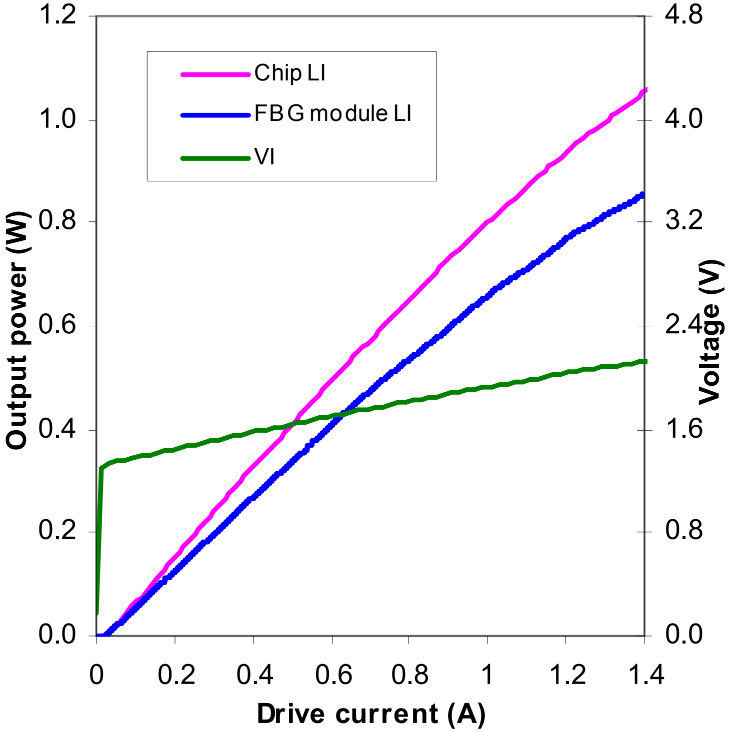
Threshold current distribution at start of test (25 °C)

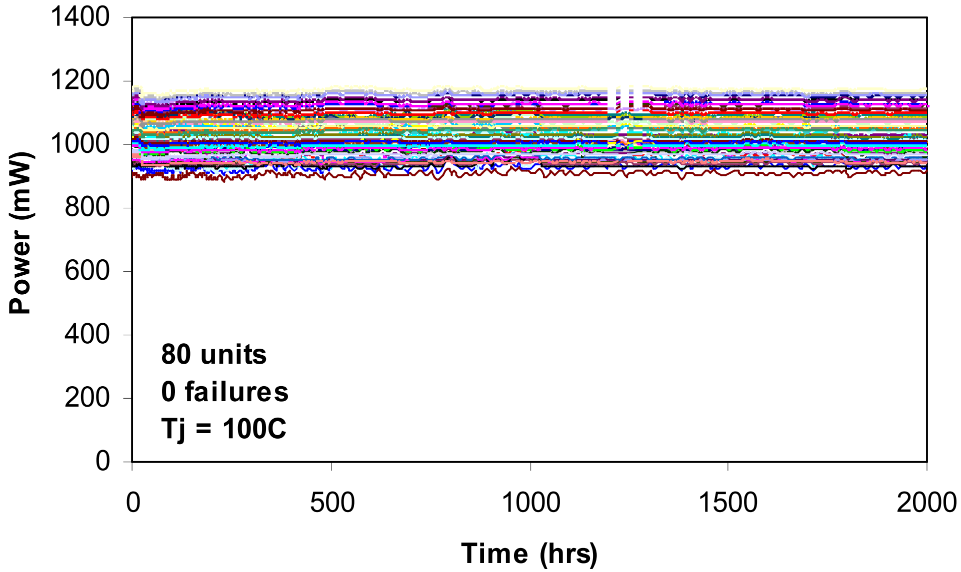
- Mean 41 mA
- Std Dev 2.9 mA

< 4% maximum change (~ 1.6 mA mean) over 2400 h at

JDSU 980nm Single Spatial Mode Pump





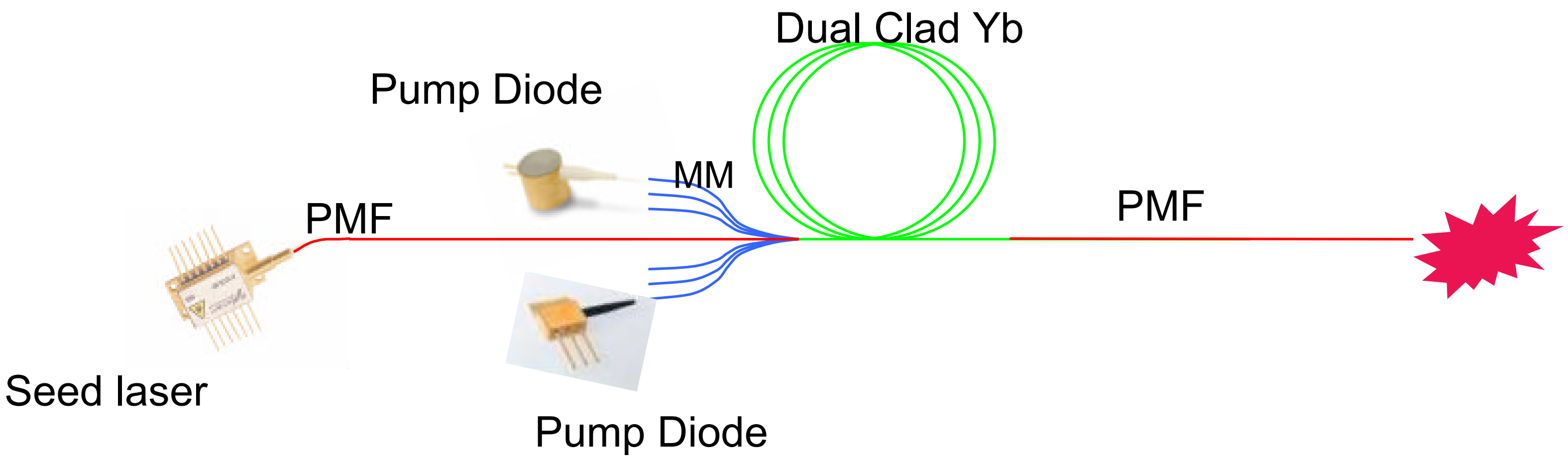


- New FBG-stabilized pump module
  - 660mW kink-free power
  - 45 FIT chip reliability at 830mW
- Mature package platform
  - 5 billion field hours
  - 5 FIT field reliability

JDSU

9xxnm Multimode Pump Diode

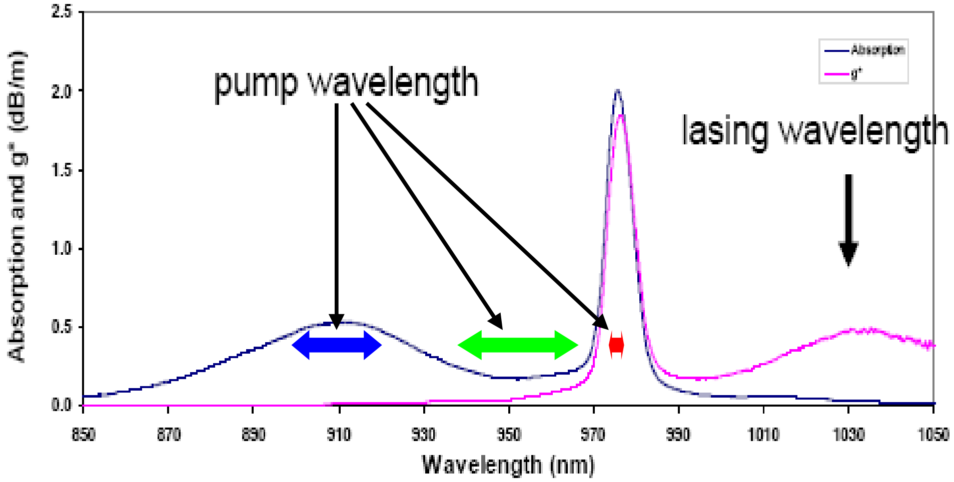
Fiber Laser: MOPA



- 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

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

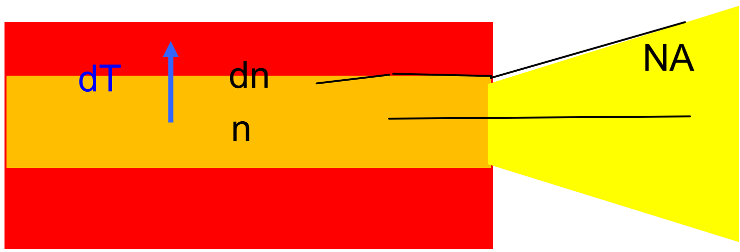
- Preferred for very high power stage

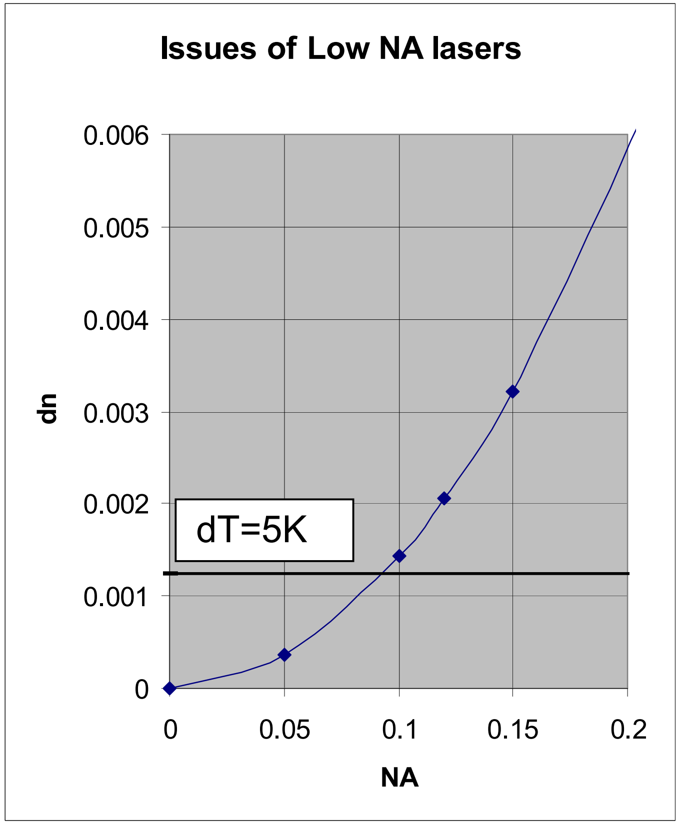
Red band (976nm)*: Highest absorption, narrow width*

- *Preferred for high gain amplifiers and q-switched lasers with short fiber (SBS)*
- *Pump diode challenge: Diode wavelength control (+/-2nm) necessary*

9xxnm Multimode Pump Diodes: Thermal Blooming at high Power

Top view of BA laser



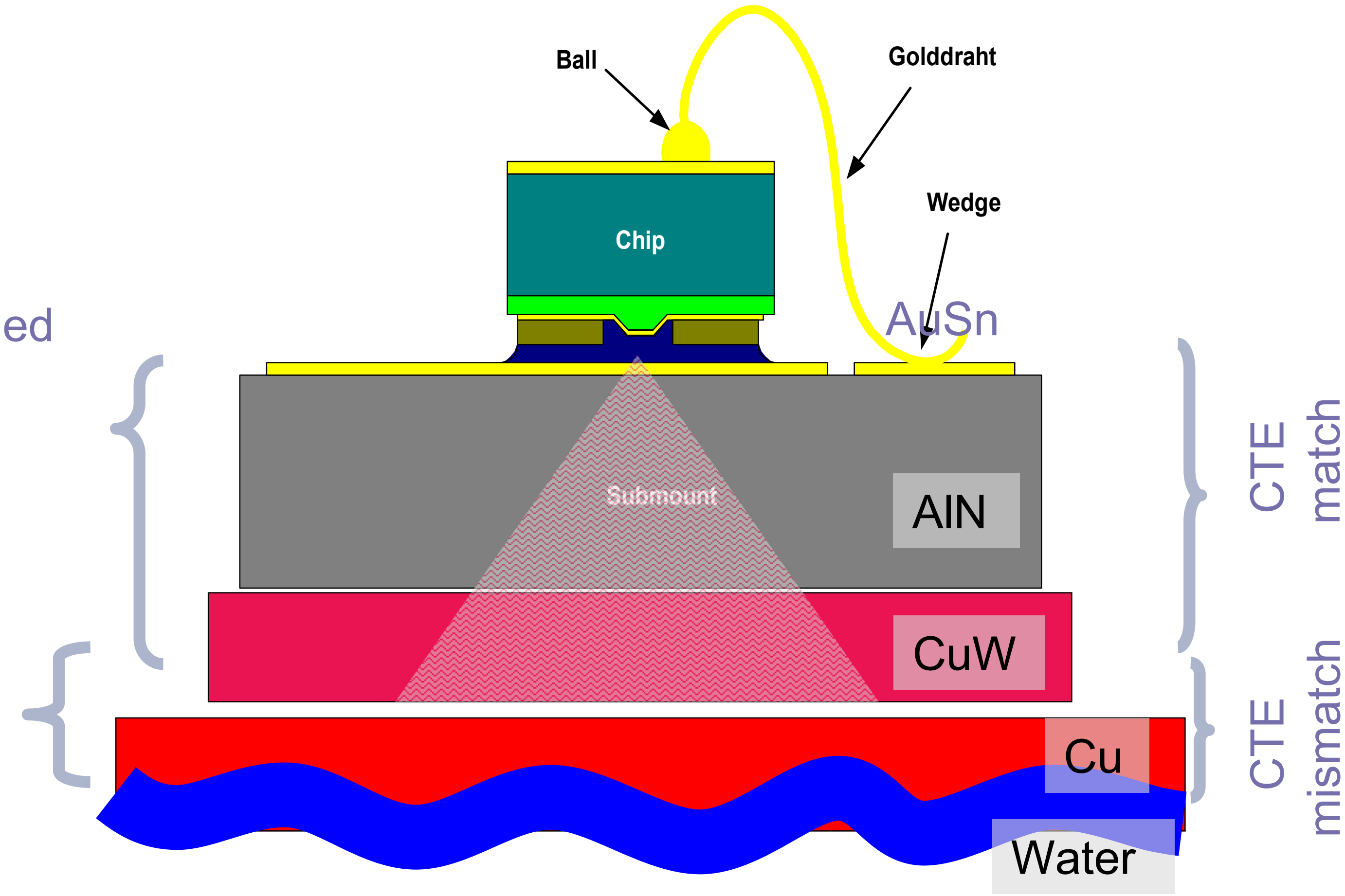


- Low NA laser
  - Achieved by low dn waveguide
- dn
  - Ridge
  - Lateral temperature profile
  - dT=5K -> NA=0.09
- Keep dT<5K

9xxnm Multimode Pump Diodes
Heat removal

Soldered to expansion matched materials for heat spreading

Mechanical pressure thermal contact to copper heatsink



9xxnm Multimode Pump Diodes: 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

Resitivity:
Series resistance
Density of States:
Free carrier absorption

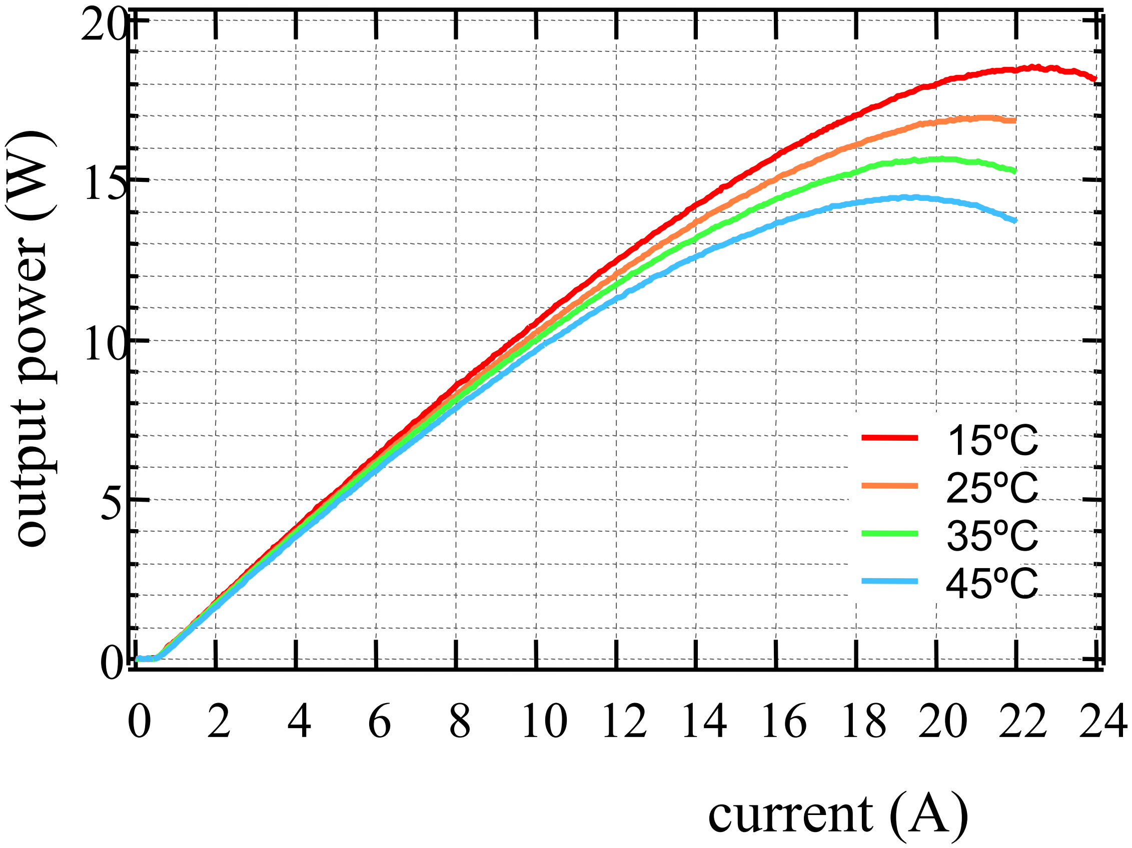
Material limits: Even after optimized mirror losses (S_f, R_f, R_b) and low threshold current.

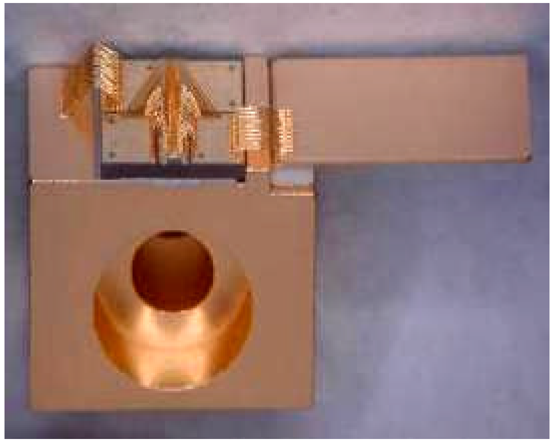
- Due to limited mobility and carrier mass there are always trade-offs in
  - doping levels (series resistance R_s vs free carrier absorption) and
  - Bandgap discontinuities (leakage losses vs injection barriers)

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)

9xxnm MM Pump Diode: CW on C-mount

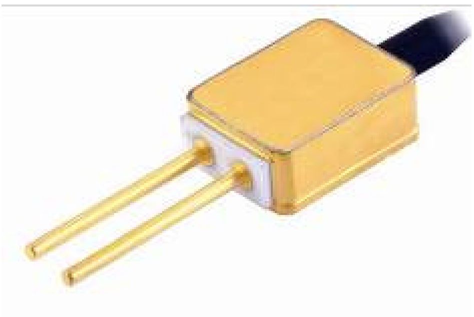


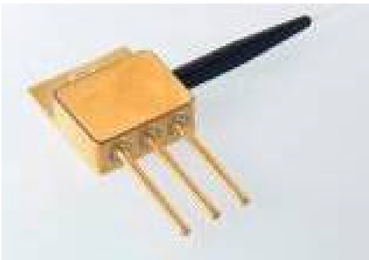


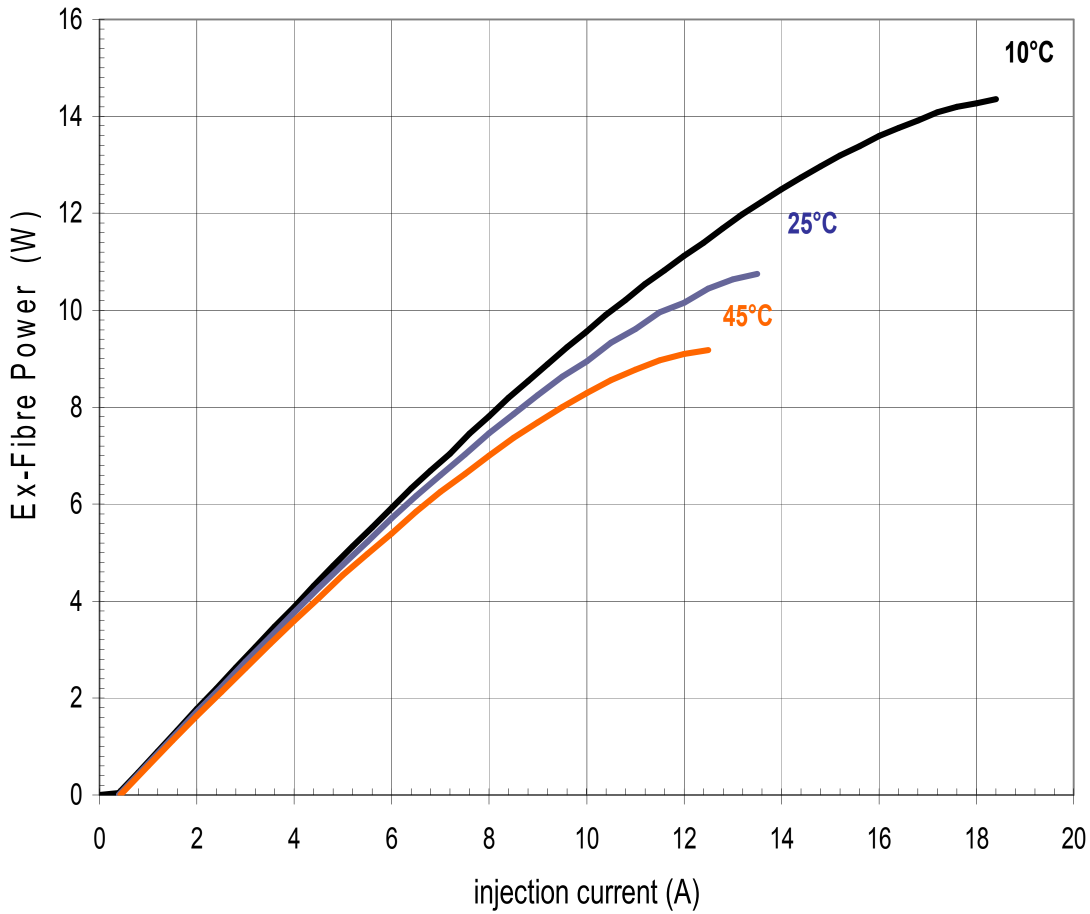
- ~90 um emission width
- 19 W CW roll over power at 15 C
- Temperature insensitive: T_o ~ 200K

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

MM Uncooled Module with >14W

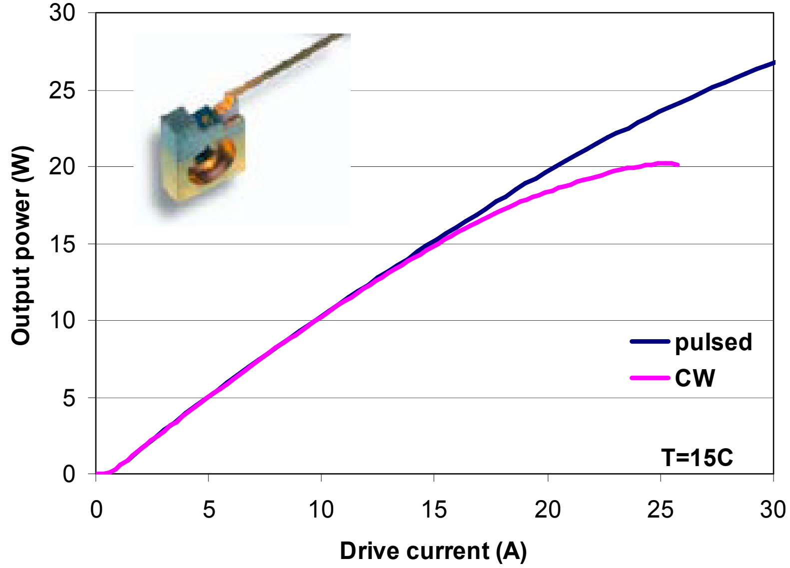


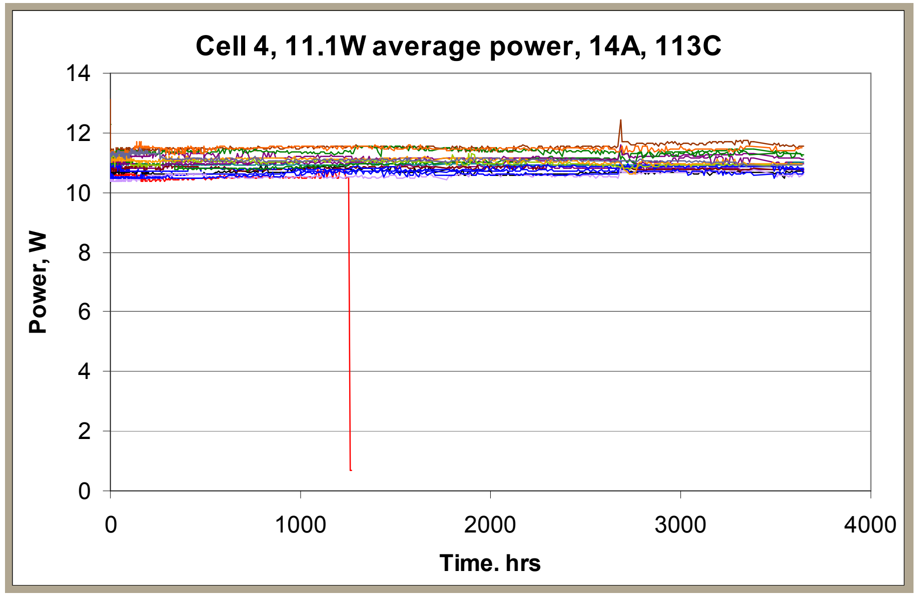


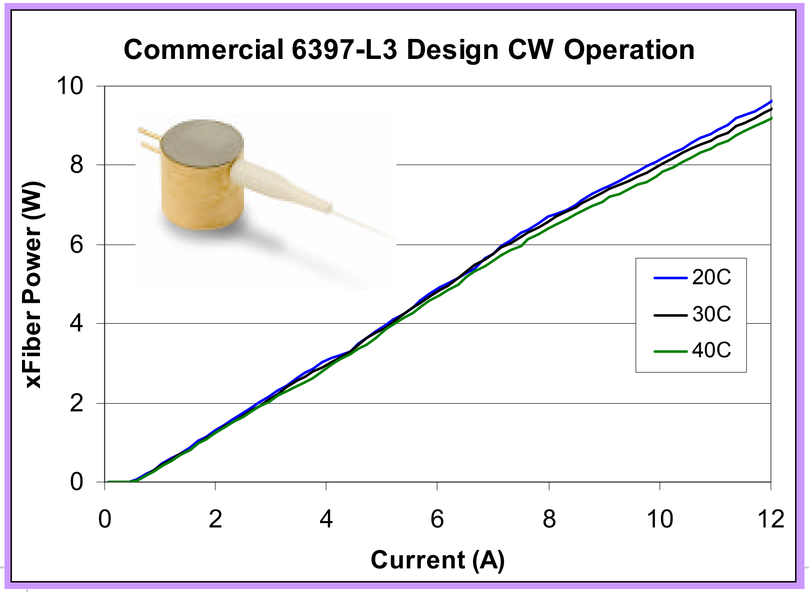


- Record Performance:
  - >14W @ 18A and 10 C T_{hs}
- Module fully qualified for industrial and telecom standards
  - 8W Industrial Product

JDSU 9XXnm Multi Mode Pump



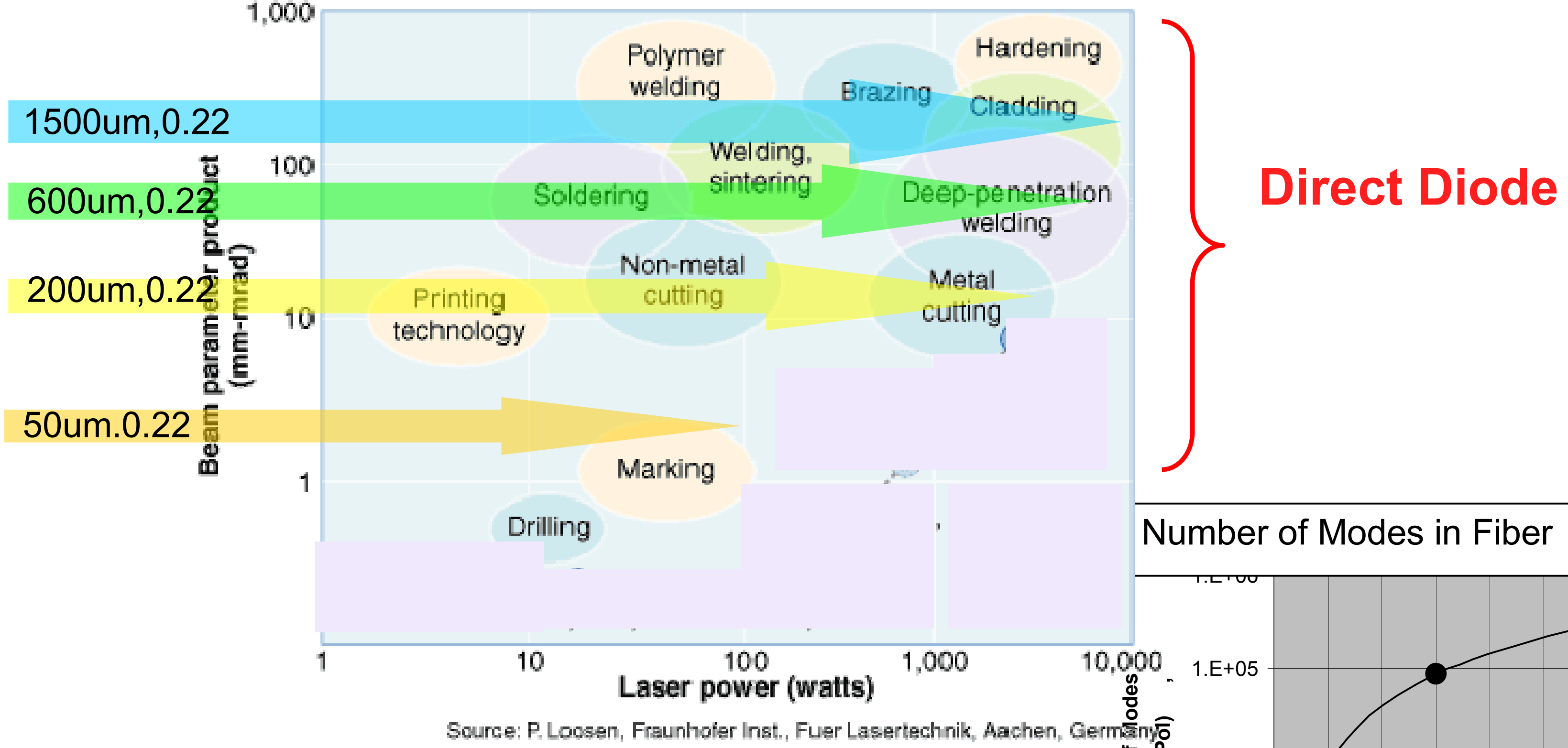


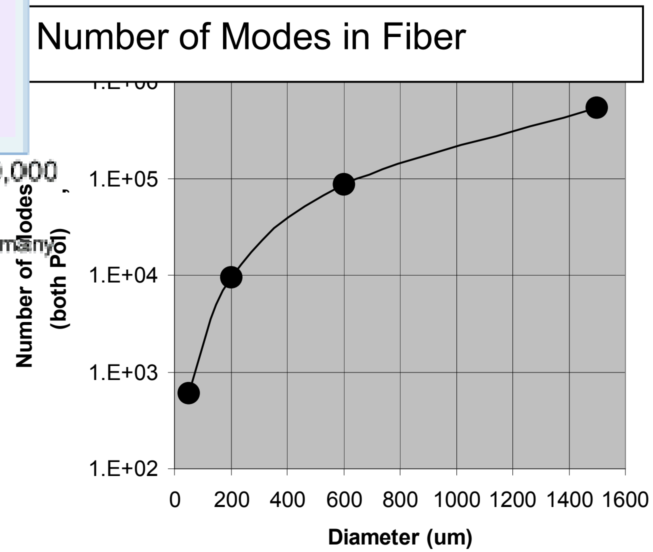


- 100µm wide aperture chip
  - 20W CW rollover power
- 105µm diameter, 0.2NA fiber
  - 8W rated power at 10A

JDSU

9xxnm Multimode Pump Diodes: Machining directly with Pump Diodes





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

High Power Pump Diode Lasers

20 years ago: Practical demonstration of Erbium Doped Fiber Amplifier:

- Triggered need for high performance pump diodes

Mature technology today:

- Mature Single Mode 980nm pump diodes available to meet telecom requirements
- Multimode 940nm Pump Diodes for CATV available

Future Challenges

- Pump diodes with even higher power and brightness for Fiber Lasers
- Pump diodes for direct material processing
  - Work needed to reduce cost and improve brightness