Pump Sources and Related Devices for High-Power Fiber Laser Systems

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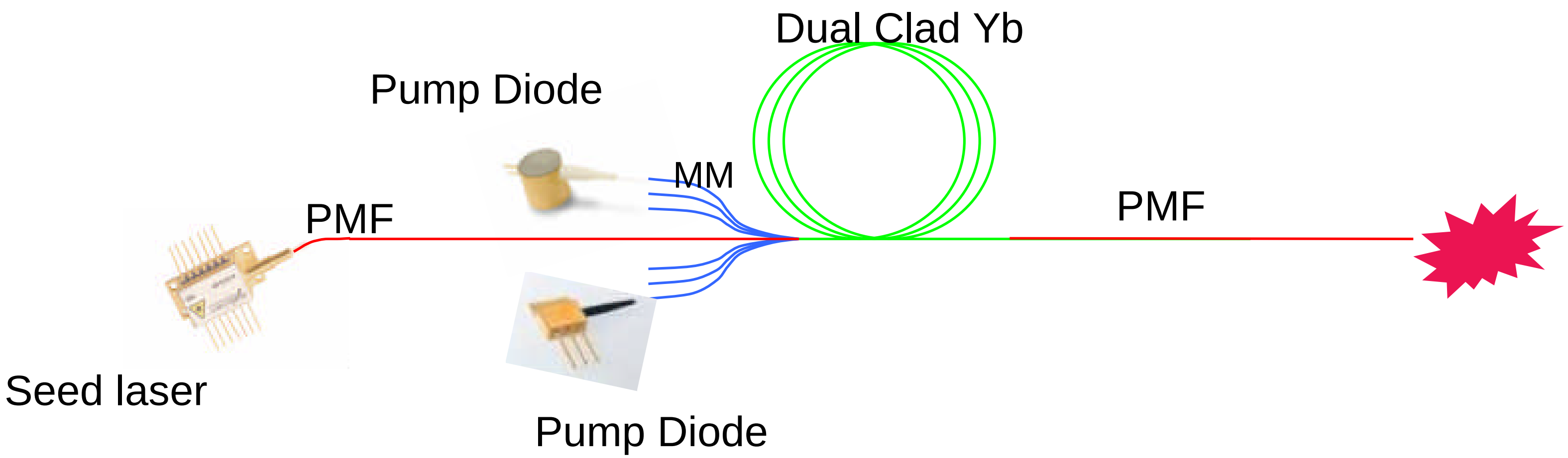
Overview

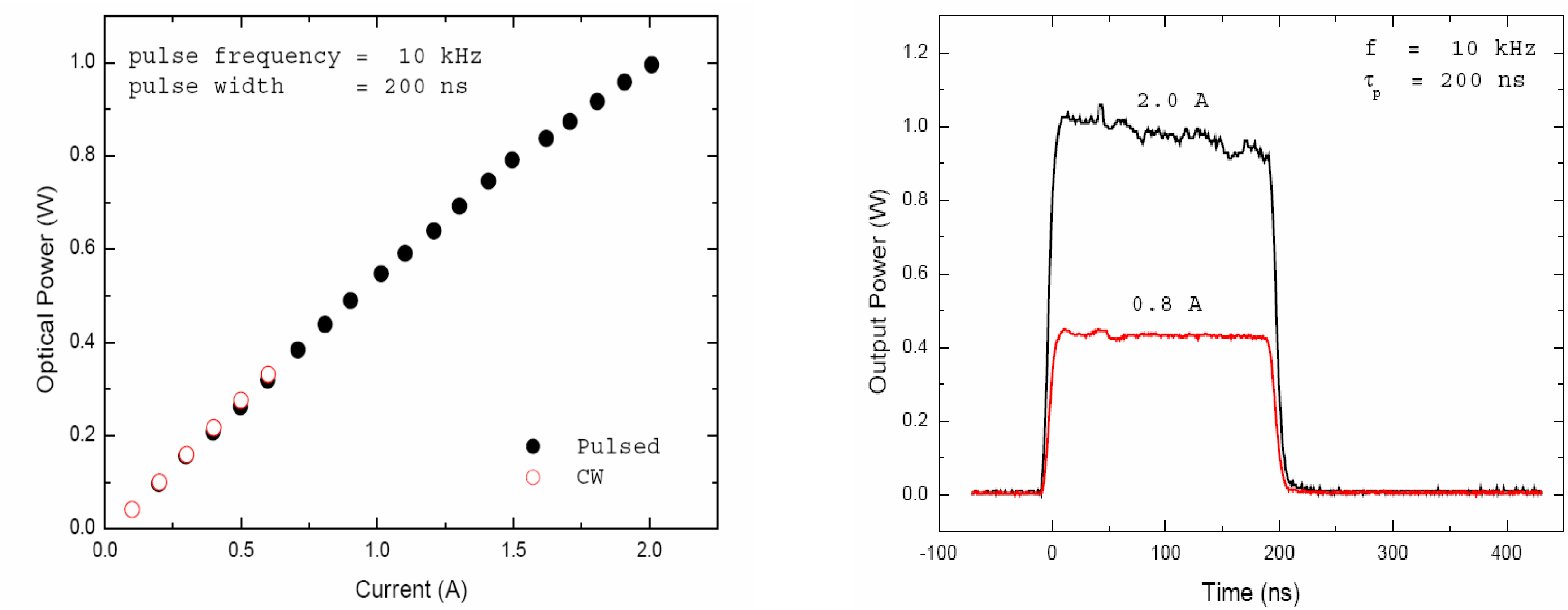
- Fiber Laser
  - MOPA: Seed laser and amplifier
- Seed Lasers
  - Switching speed
- Pump Diode
  - Yb fiber wavelength bands
  - Diode heat removal
  - Pump power injection
  - Cost
- Reliability
  - Diode reliability
  - Fiber reliability
  - System robustness
- Acknowledgement: B. Schmidt (Bookham), T. Strite (JDSU), K. Eberl (Lumics)

Fiber Laser: MOPA



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

1060nm seed laser

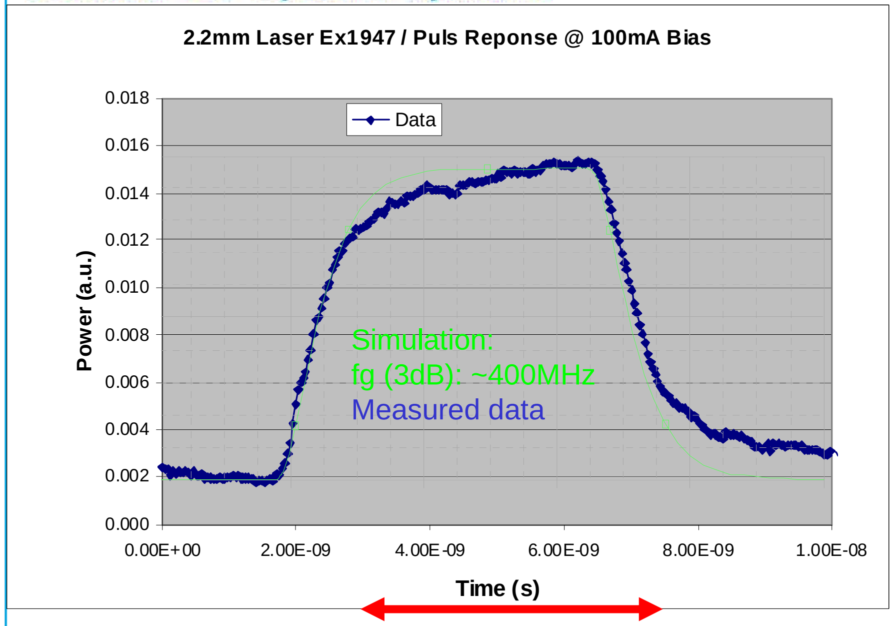


- Pump laser diodes have excellent dynamic characteristics in standard pump butterfly package

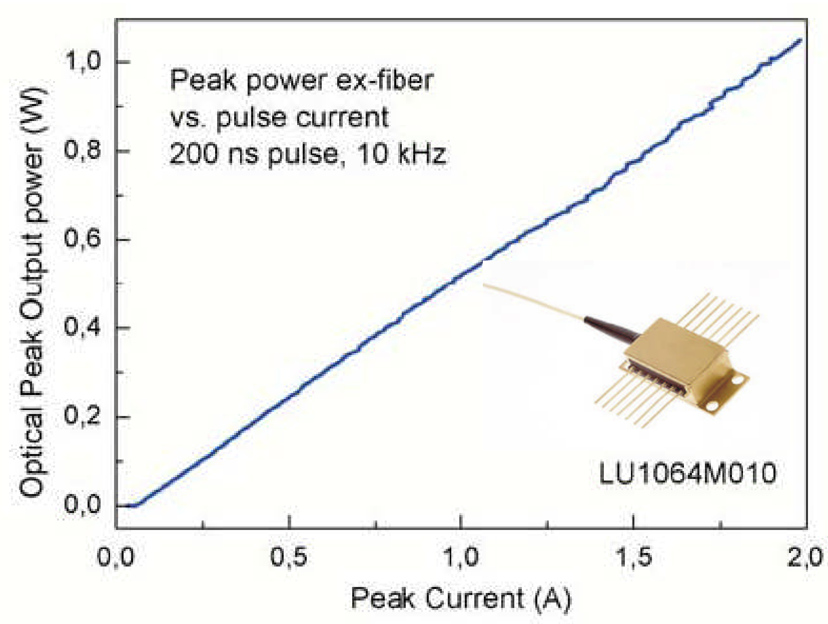
Lumics

Devices for Optical Systems

1W 1064nm SEED-laser module



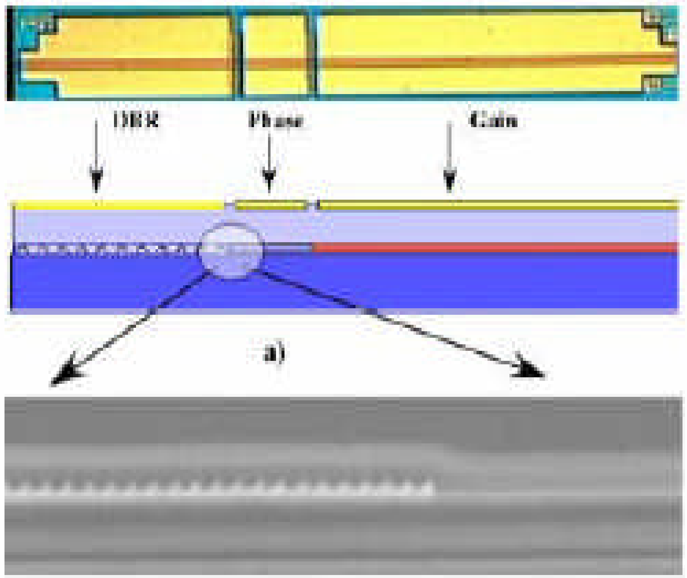
5ns



- Wavelength 1060 - 1080nm
- Short pulse operation 5ns - 1µs
- Up to 1W peak power
- Cooled 14-pin package
- Very powerful chip design
- Single mode fiber pigtail

Also available with external stabilization and kHz bandwidth

Seed Lasers
1060nm DFB



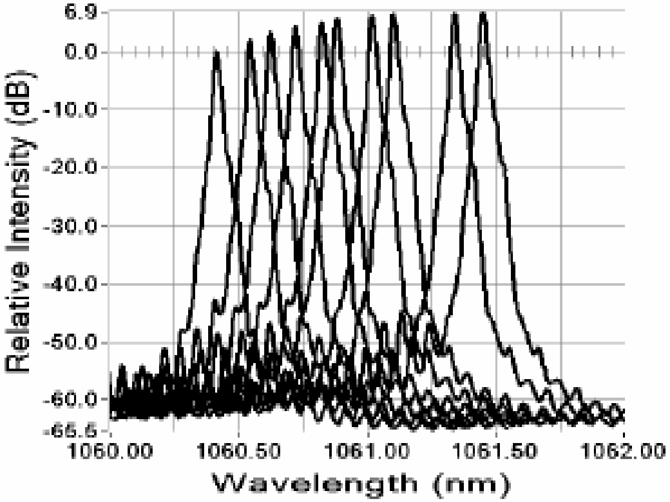
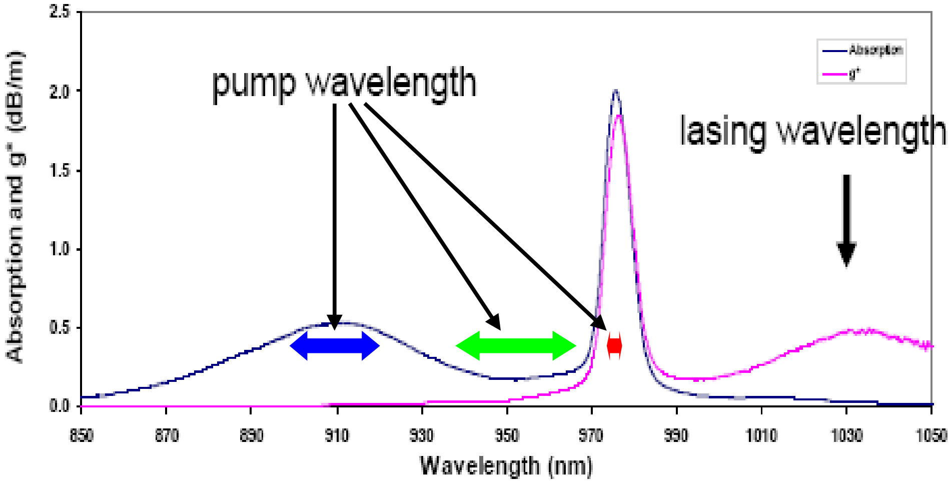


Fig. 5 Optical spectra of a DBR laser at different drive currents

2005, C. E. Zah et al, Corning

- DFB has stable, narrow spectrum and can be switched on and off at high speeds

Yb fiber wavelength bands



Yb: Glass fiber absorption and emission spectrum

Wide pump band: 870nm to 980nm

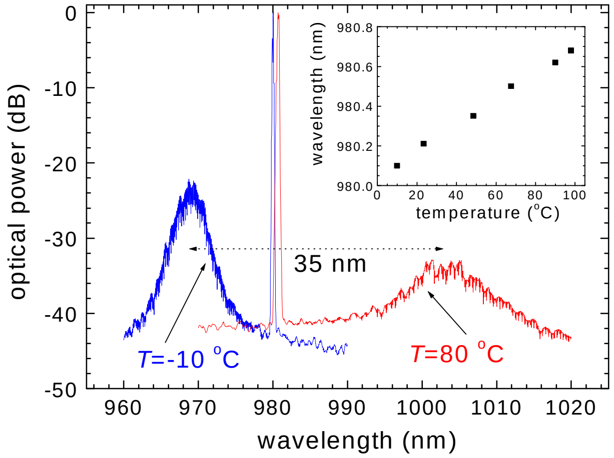
Red band (976nm): Highest absorption, narrow width
- Preferred for high gain amplifiers and q-switched lasers with short fiber (SBS)
- Pump diode challenge: Diode wavelength control (+/-2nm) necessary

Blue band (915nm): Good absorption, wideband
- Preferred for lower power stage
- Pump diode requirement: Good reliability at 920nm. Possible

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

Yb fiber wavelength bands
976nm band

- Single mode pump diode external grating stabilization
  - Established acceptance (reliability) through tremendous effort



2001, Bookham S. Mohrdiek et al.

- Pump diode wavelength temperature shift
  - Free running FP diode: 0.3nm/K
  - DFB: 0.1nm/K

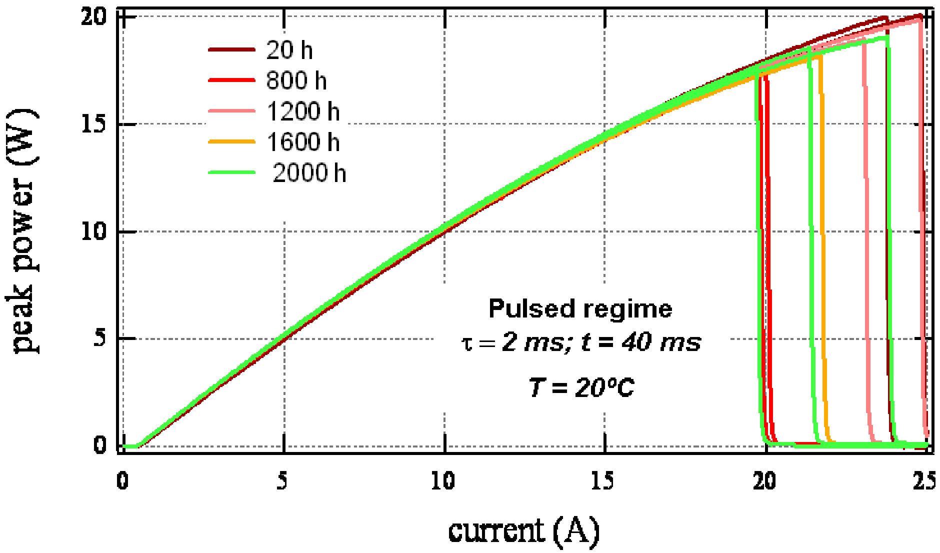
  -> External grating for +/- 2nm stability
- MM external stabilization: Very active field and good progress
  - Nevertheless: Very challenging
    - locking range, efficiency, noise and reliability
    - Cost

  ->976nm band: Most likely limited for very special applications

Yb fiber wavelength bands
920nm band

- Pump Diode Challenge: Reliability at 920nm
  - Feared: COMD degradation at high operating power

COD level versus time @ 915nm wavelength



Stable COD level at around 22A injection current (in average) equivalent to 17.5W out of a ~90um aperture (over 2000h test time at 9A, 25 °C)

2006, Bookham, B. Schmidt et al.

- "920nm Reliability Challenge" solved through facet passivation techniques

-> 920nm Band: Preferred for high absorption cross section applications

Diode heat removal
Diode power conversion

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

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

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

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

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

Doping levels
1. Series resistance
2. Mainly free carrier absorption

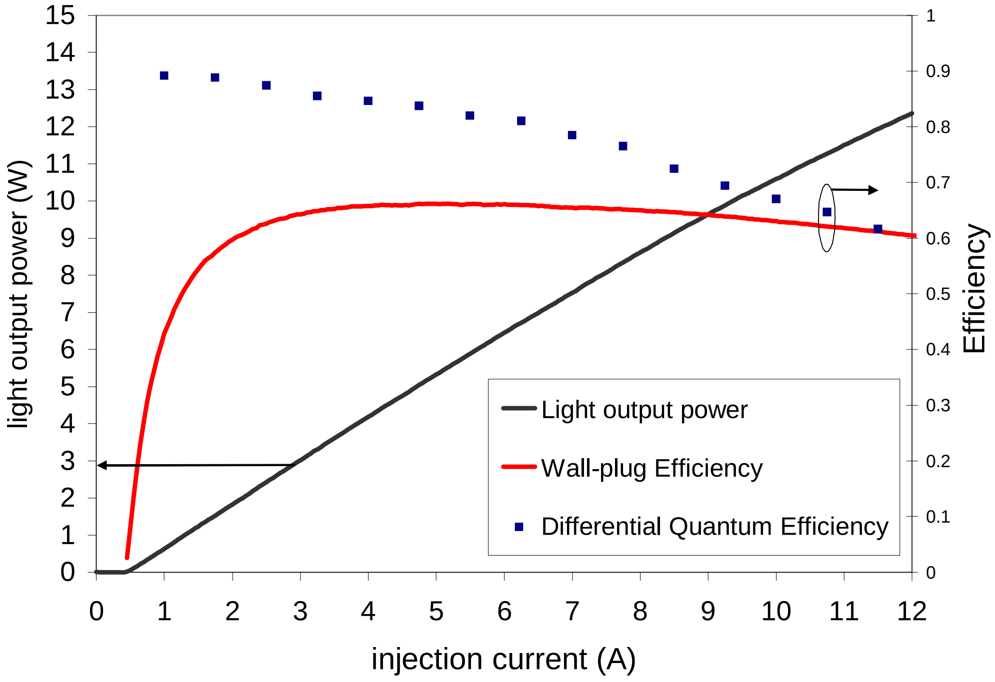
Material limits: Even after optimized mirror losses (S_f, R_f, R_b) and low threshold current.

- 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)

Diode power conversion



CW-operation
λ= 920 nm

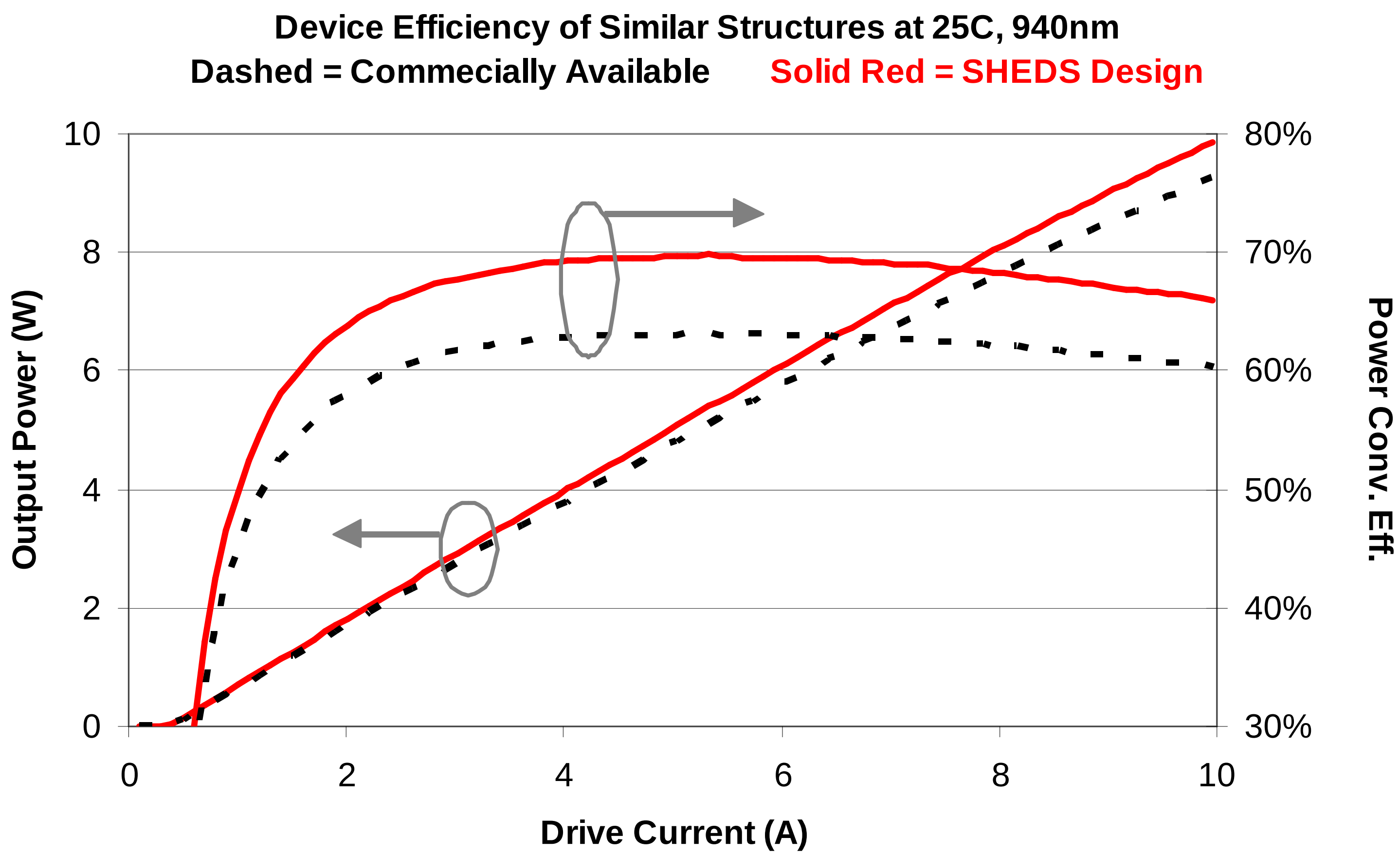
Bookham: SES8-9xx-01 Product

>12 W @ 12 A in CW-operation @ 20°C

~67% maximum wall-plug efficiency (~65% @ 9 W)

which results in 50-57% overall wall plug efficiency out of the module

Diode power conversion

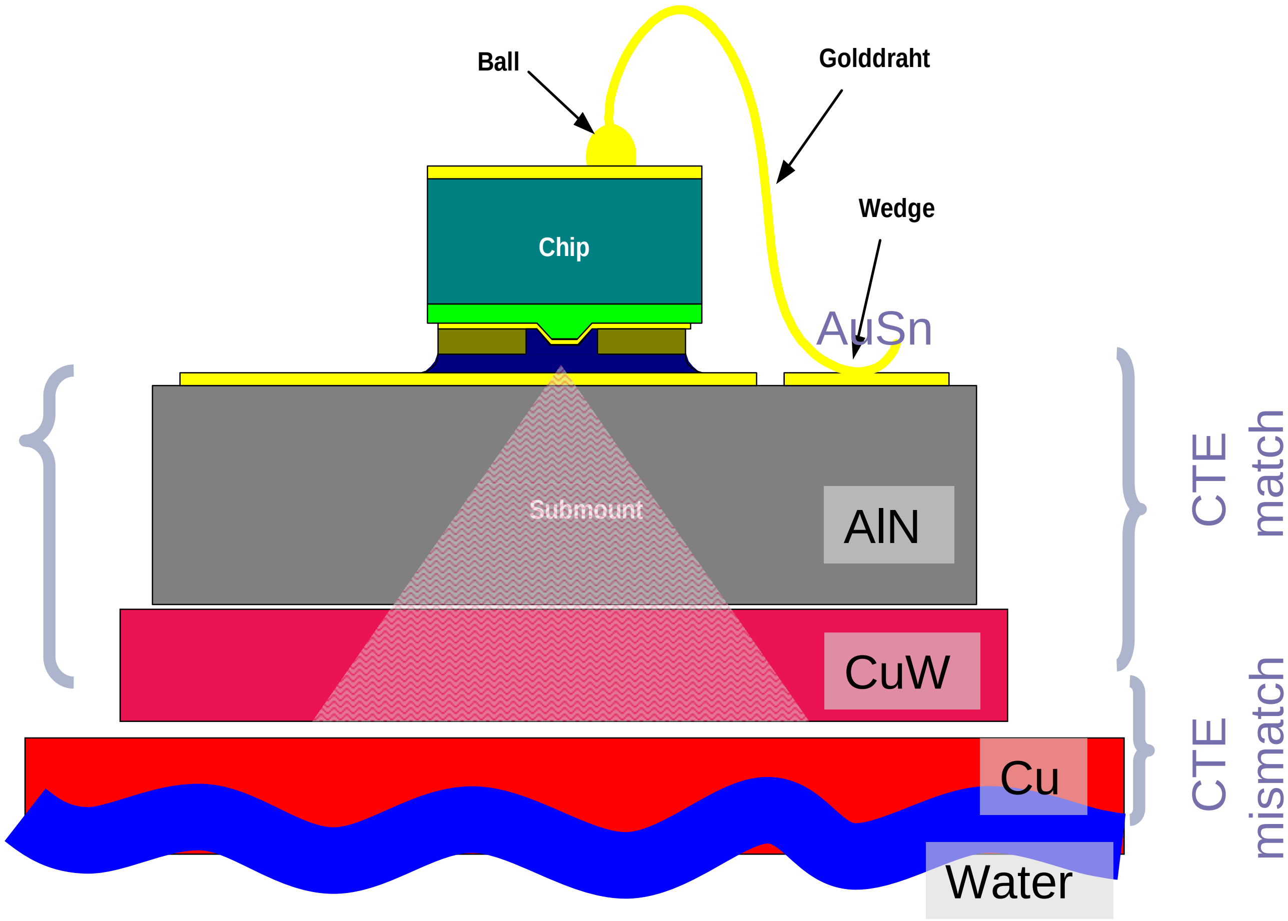


Research funded by DARPA SHEDS program promises power conversion efficiency improvements in future fiber laser pumps

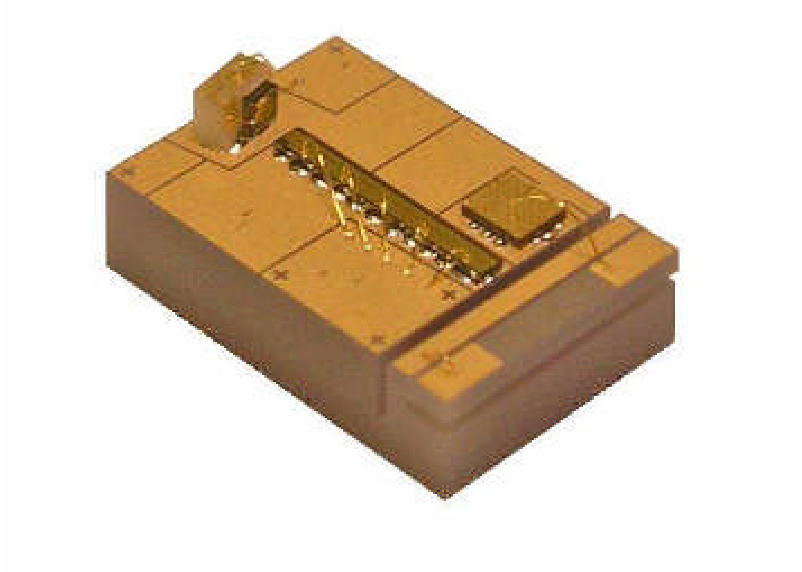
Diode heat removal
Single Emitter: Heat spreading

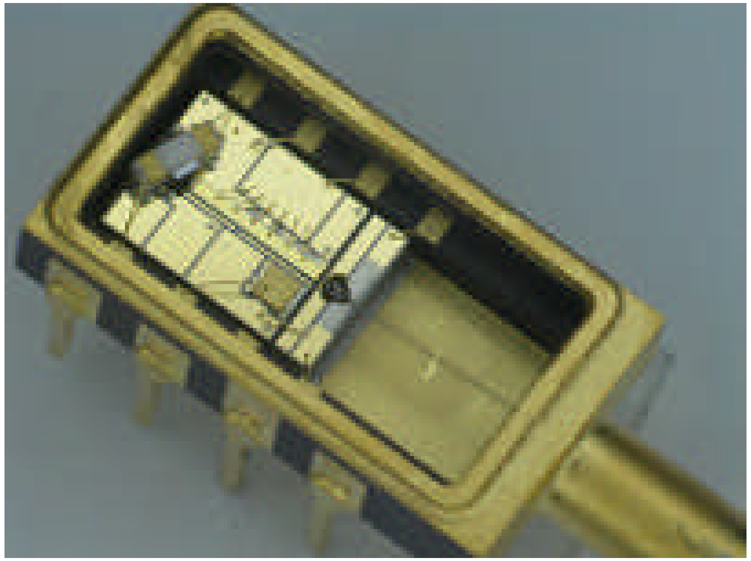
Soldered to expansion matched materials for heat spreading

Mechanical pressure thermal contact to copper heatsink



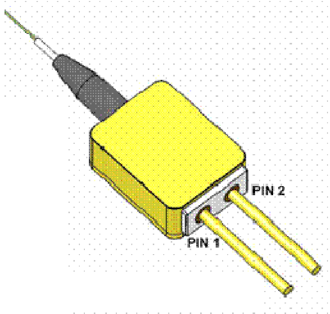
Telecom technology

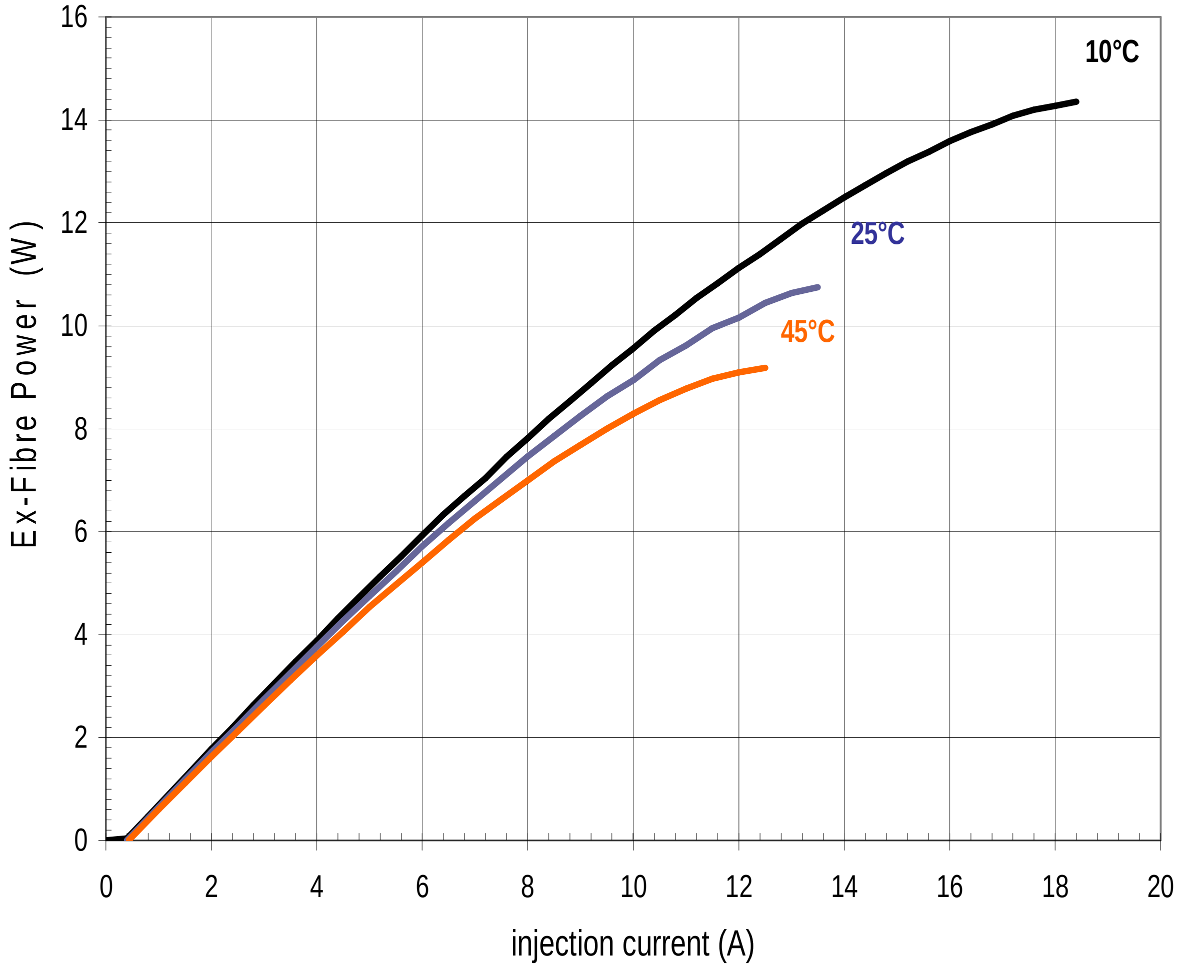




- Technology: Monolithic optical platform (AlN) with
  - Laser diode, soldered with AuSn
  - Fiber tip attached to monlolithic optical platform
  - Monitor diode and thermistor
- Performance
  - Very stable laser facet/fiber tip fixture
  - Small size and low cost

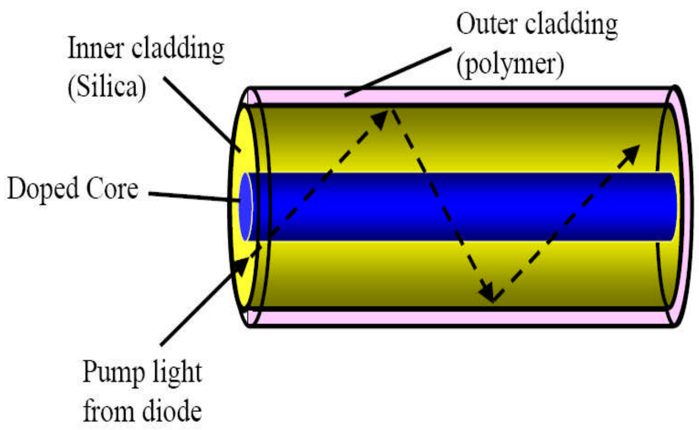
MM Uncooled Module with >14W

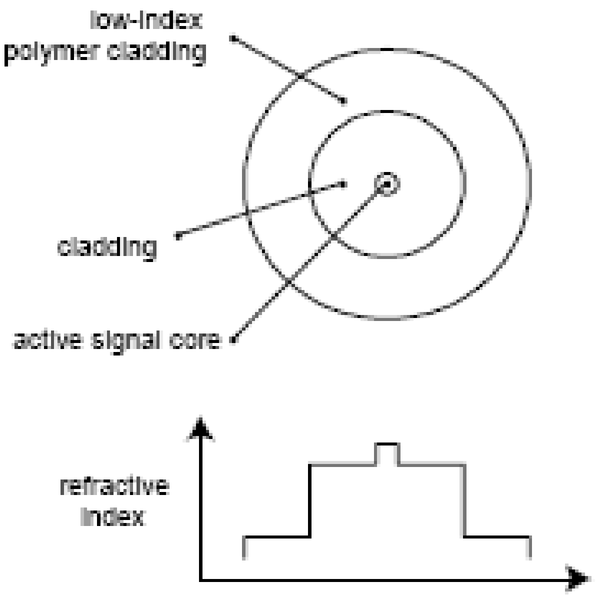




- Record Performance:
  - >14W @ 18A and 10°C T_{hs}
  - Standard MU package
- Module fully qualified
- MSA with EM4
- For 100um pigtail with NA=0.22 or NA=0.15 (same performance)

Pump power injection
Coaxial dual cladding

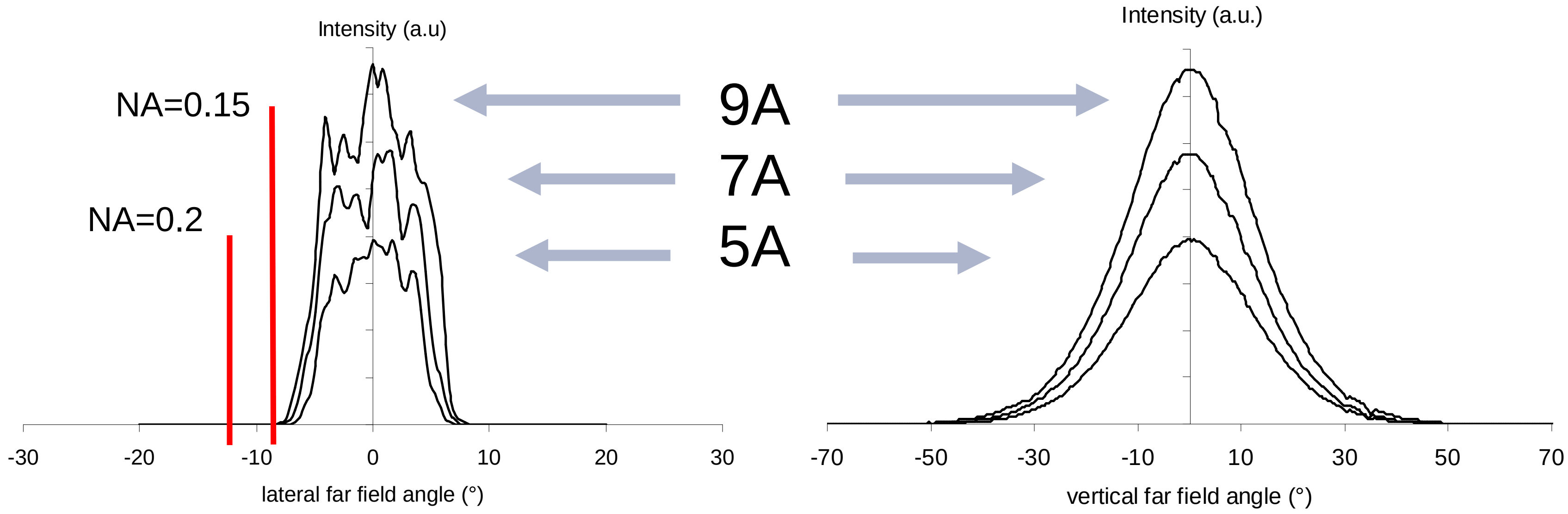




Coaxial cladding

400um, NA=0.46: 150'000 modes

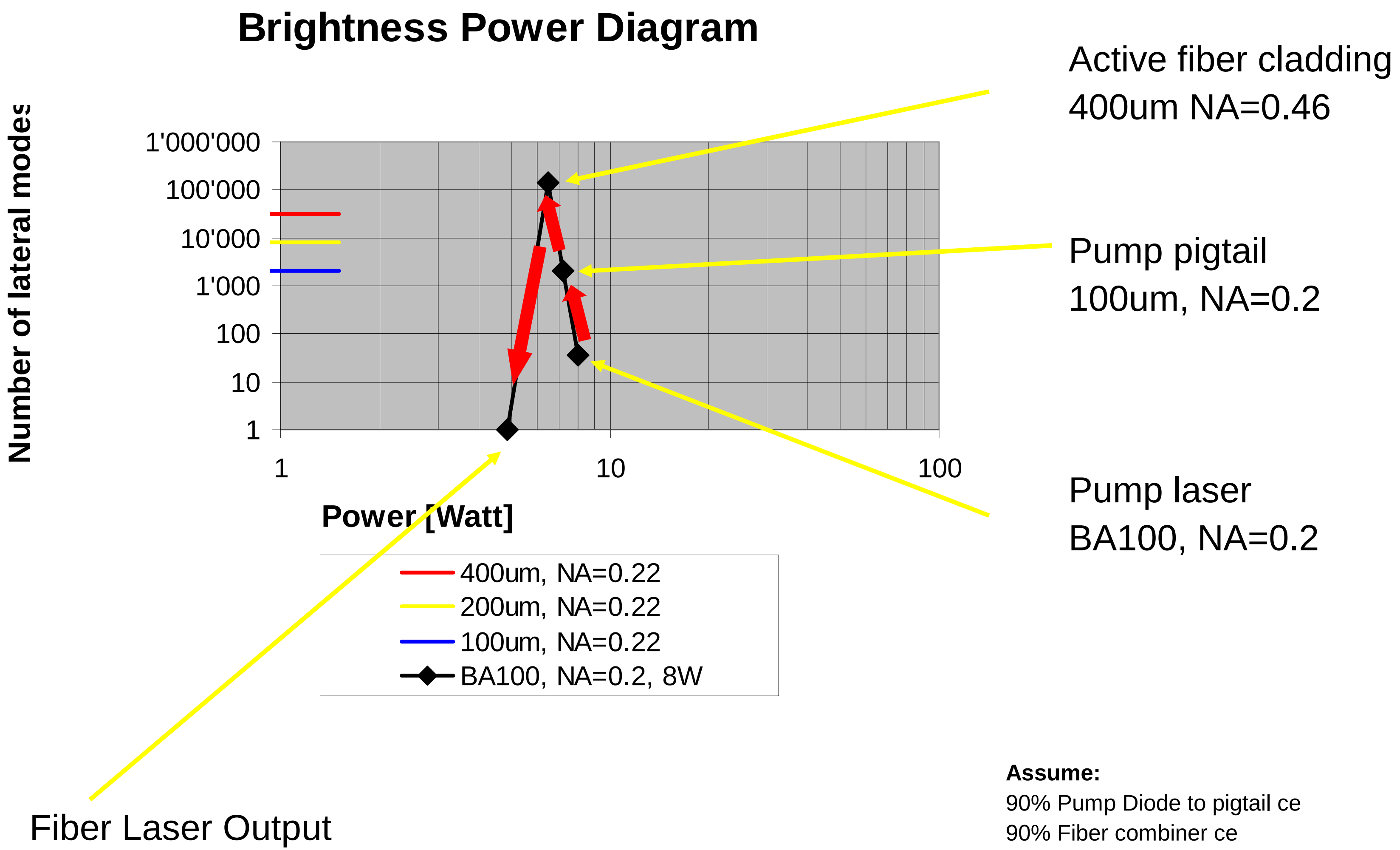
Pump power injection
MM Beam divergence



- Stable beam
  - Vertical: 0.3mm mrad: Single lateral Mode
  - Lateral: 7.5mm mrad: 25 lateral modes

  - Overall Beamquality: 25 modes
  - Coupled in 100um NA=0.2 fiber: 2000modes (10mm mrad)

Pump power injection
Brightness-Power Diagram



Assume:
90% Pump Diode to pigtail ce
90% Fiber combiner ce
75% Fiber laser ce

Fiber combiner (6+1)*1, (2+1)*1
Free space combiner

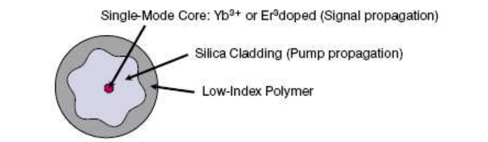


Figure 2 Cross-section of double-clad optical fiber for cladding pumping.

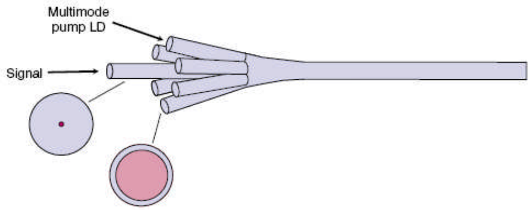
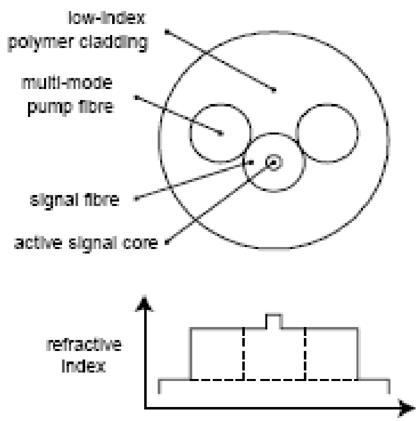
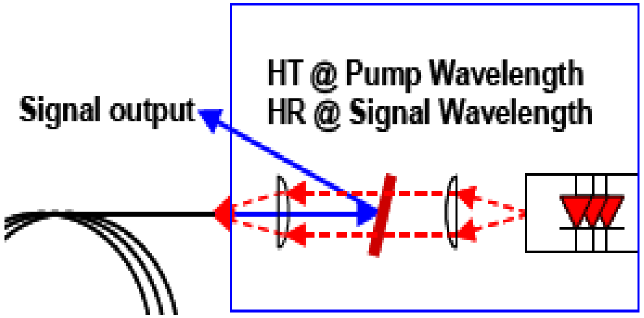


Figure 3 Schematic of tapered fiber bundle.





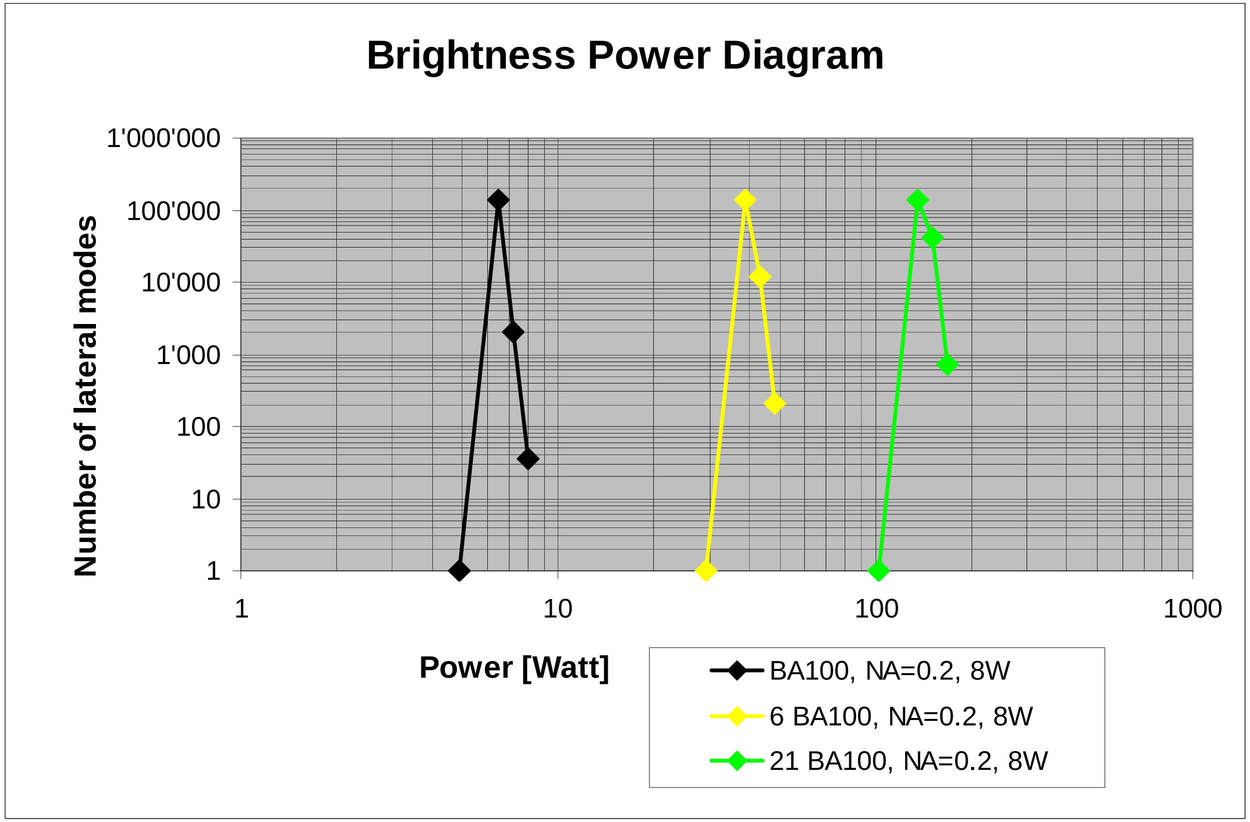
(6+1)*1: Fused

(2+1)*1: Proximity

- Fiber combiner of pigtailed single emitters
  - Space multiplexer for signal/pump separation

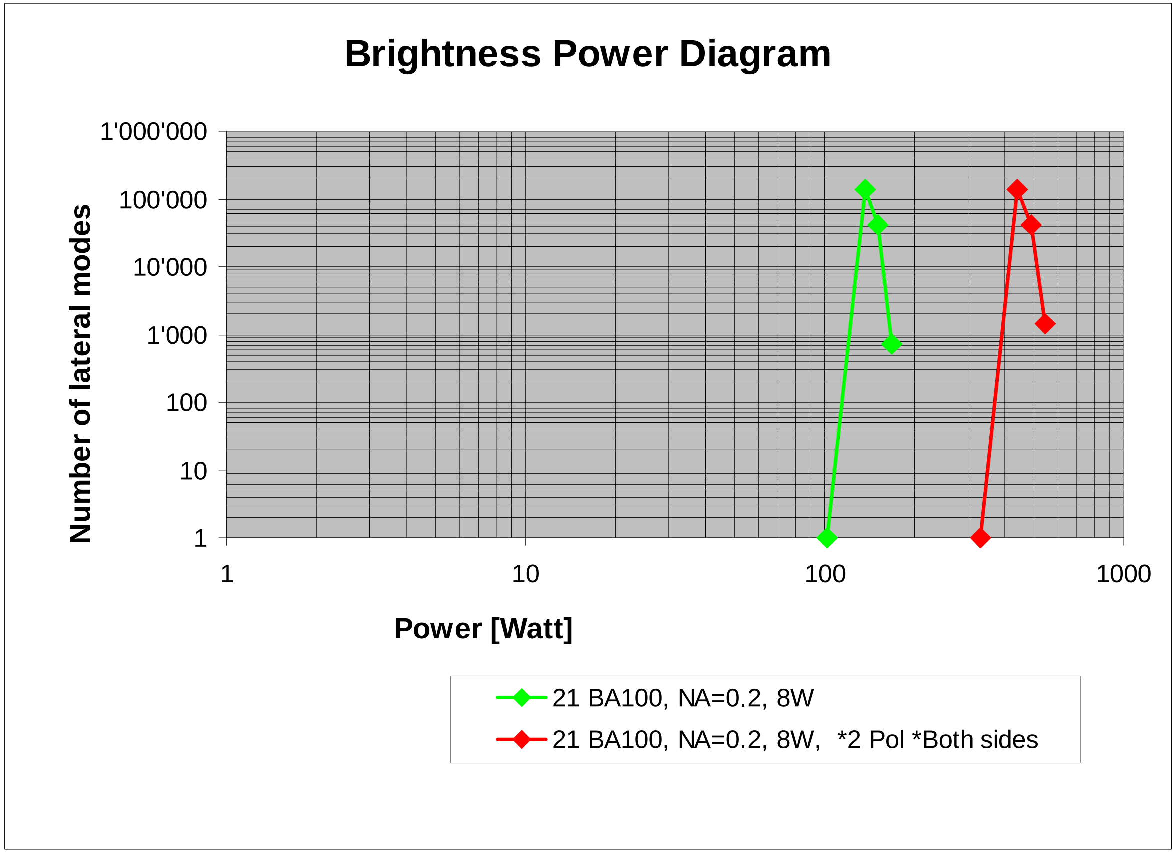
- Free space combiner of pump diode stack
  - Wavelength multiplexer for signal/pump separation

Pump power injection
Fiber combiner



- Fiber combiner modal window gets smaller with increased bundle size

Pump power injection
Polarisation combiner, both side pumping

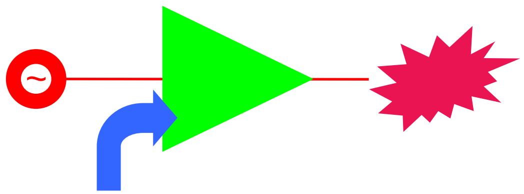


To inject 84 pump diodes through 21 fiber bundle:

- polarisation combining in pump diode package and
- co and counter propagating scheme

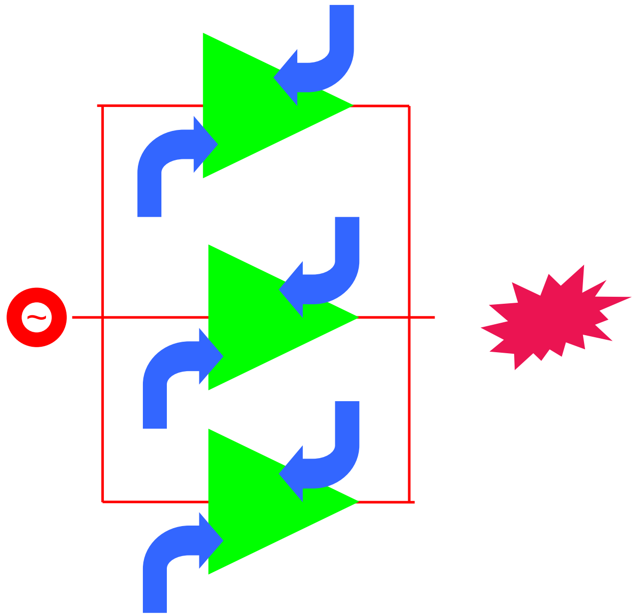
Pump power injection
Series and parallel addition of fiber amplifiers

- Single stage

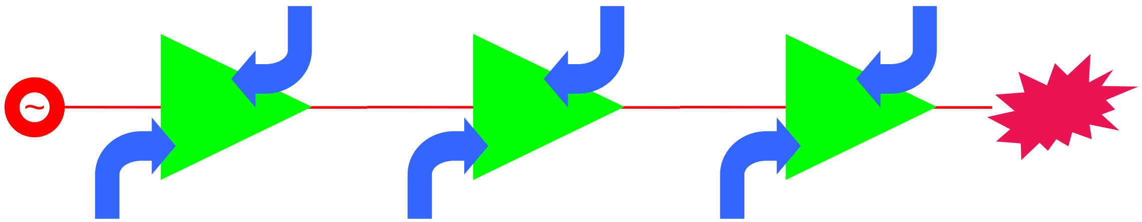


Scaling:
Cost proportional to power

- Parallel



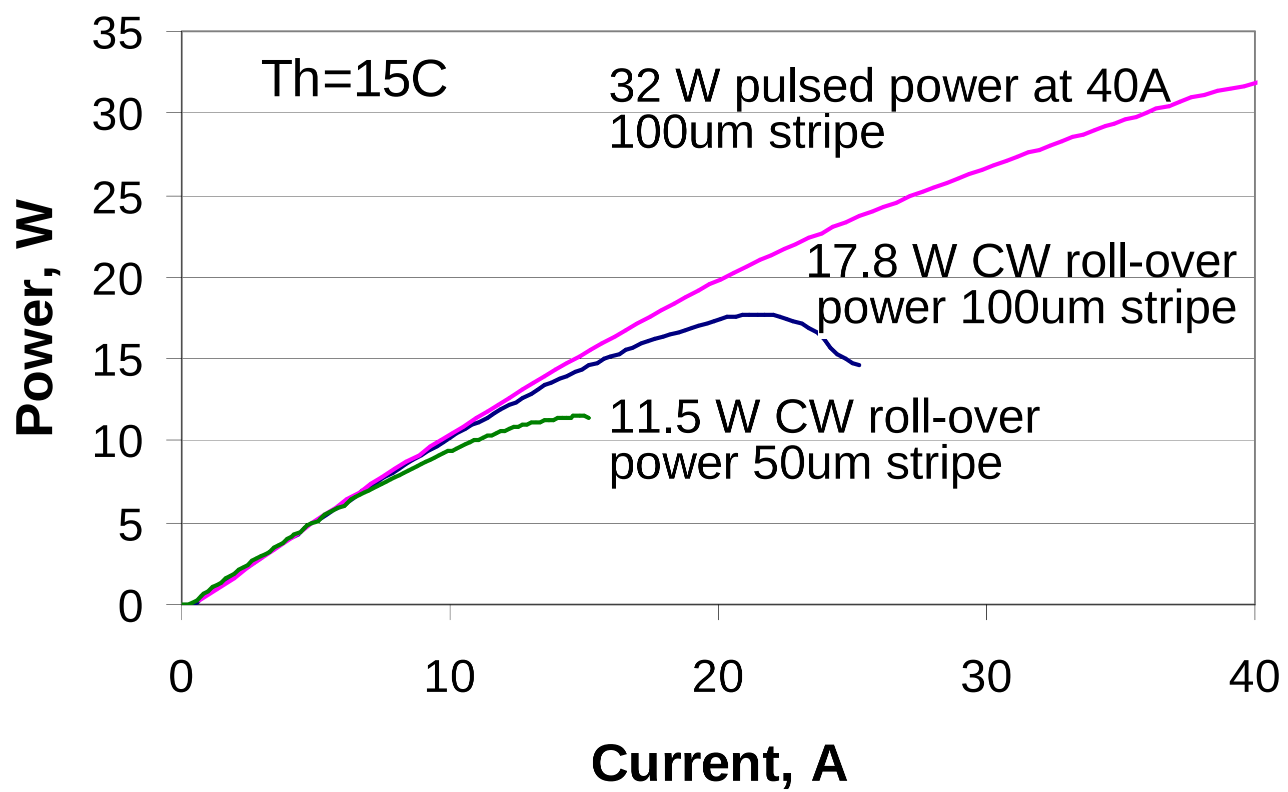
- Serial



Pump power injection
Pump Diode: $/Watt

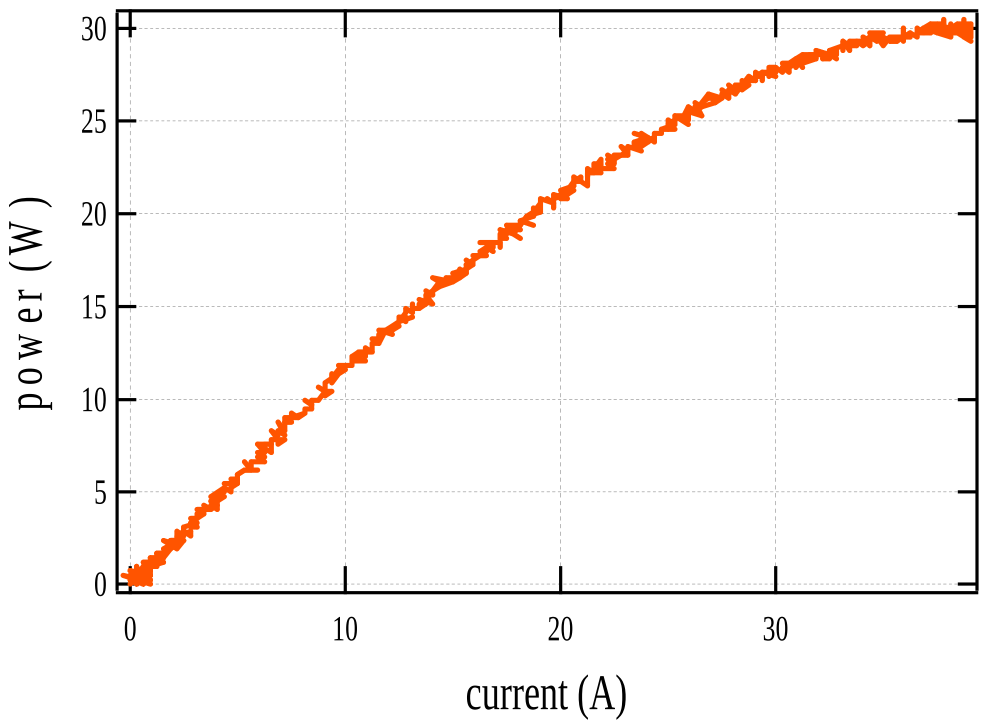
- Ultimately 10$/W as a goal for very large volume
  - Still need factor of approximately 5 from today (to be a good business by itself)
- Learning experience from telecom pumps to reduce cost
  - Large fully absorbed fabs, large sunk R&D cost
  - Manufacturing experience:
    - Volume: One platform for all parts
    - Hybrid assembly: Automatic and manual
  - At 20% improvement per year: Need another 7 years
- Pigtailed package: For 200 to 300$?
  - Need 20W to 30W in pigtail
- Increase pump power per chip
  - Fundamental brightness limits? Not reached yet!
  - Thermal limits can be streched, (longer laser chips)
- Task for fiber community: Find best match between pump diode pigtails and fiber combiners
  - Standard today: 100um, NA=0.22
  - Move to 100um, NA=0.15 > larger combiners
  - Move to 200um or even 400um, NA=0.15: Higher pump power per package
  - From fibers to waveguide tapes?

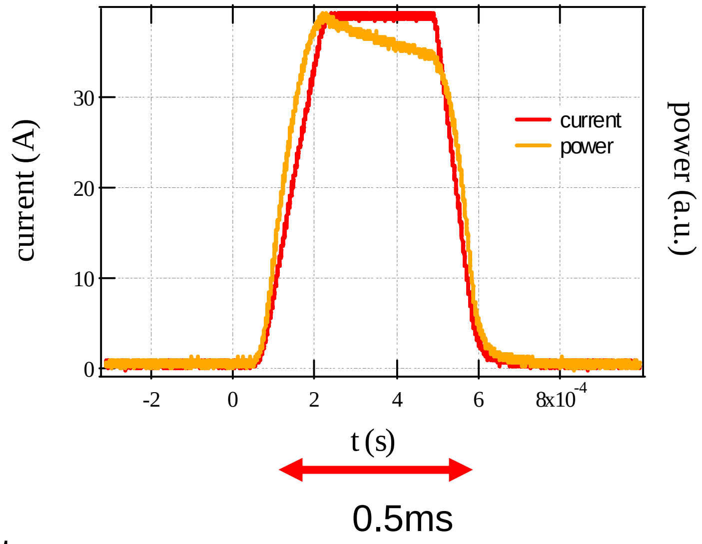
In search of fundamental limits



With thermal limit removed, broad-area heroes hit single-mode telecom 980nm pump rated power density

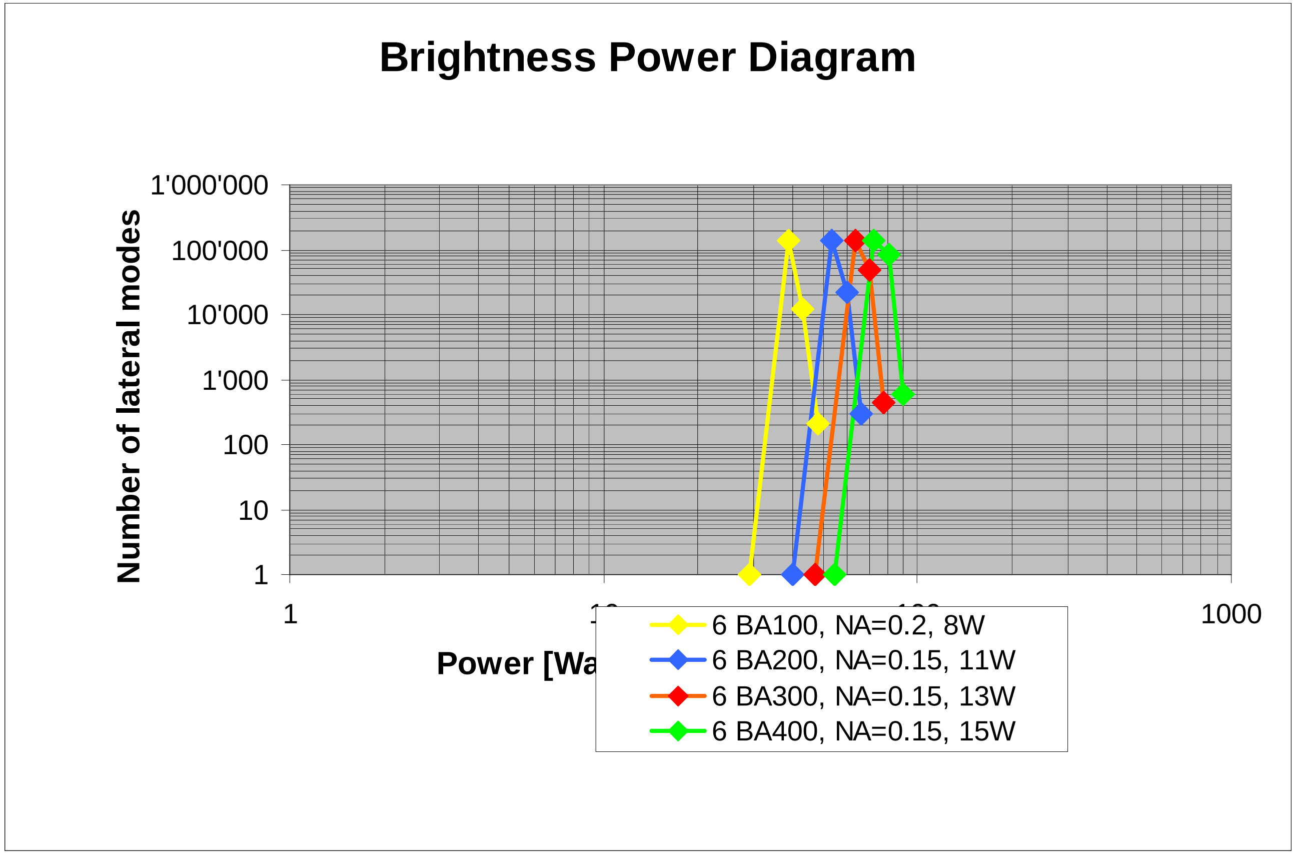
Brightness limit: Not reached yet





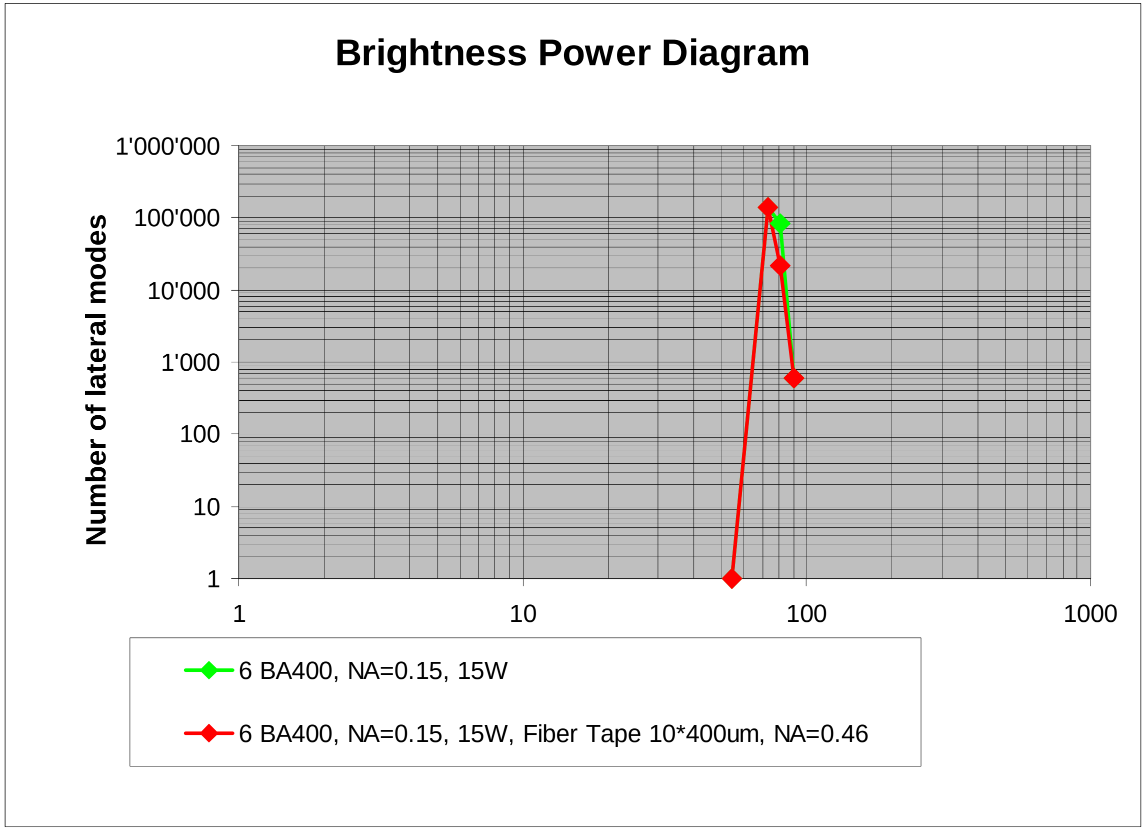
- 0.5ms 40A pulse: 30Watt from 90um BA single emitter
- Improve CW power by better thermal performance
  - Longer chip
  - Higher efficiency

Pump power injection
Low NA, wide single emitters



- Increase power of single BA emitter by increasing emission width
- (6+1)*1 combiners commercially available for 100 and 200um fibers
- 300 and 400um should be feasible

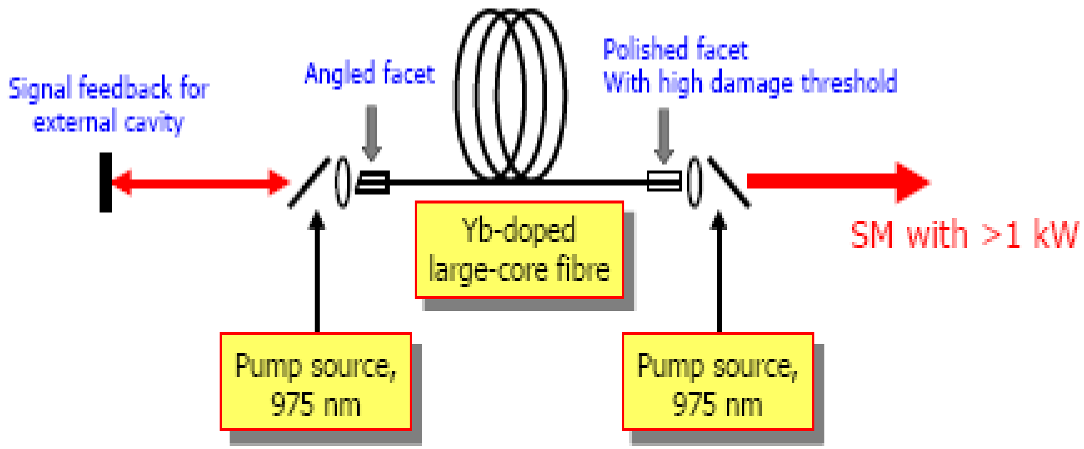
Pump power injection
Improve match of pump diode and waveguide



- Innovation needed:
- Improve match by going from round pigtail to high NA fiber tape pigtail (e.g. 10*400um, NA=0.46)

Pump power injection
Bar stacks: Why?

Stacks to further reduce $/Watt!



Stacks

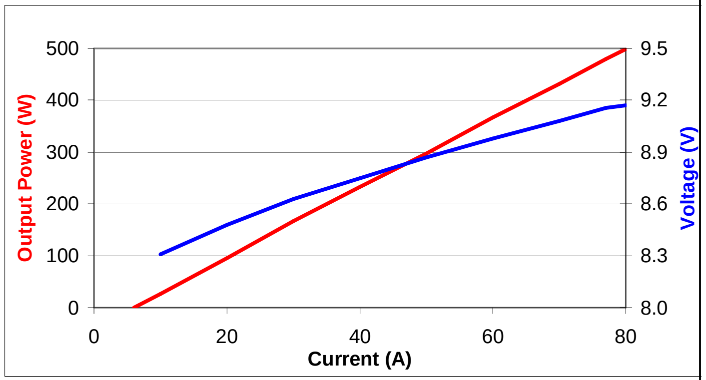
- Open package
- Free space optic combiner
  - Opto-mechanical precision
- High heat density
  - MCC coolers with high water flow velocity
  - Bar needs to be solderred to MCC
  - Water and bar at same voltage potential. Bars and MCC in series
- Reliability
  - MCC limits lifetime (degradation by flow-erosion, cavitation and electro-erosion)
  - MCC has different cte than bar. Strain for hard solders or unstable joint for soft solders

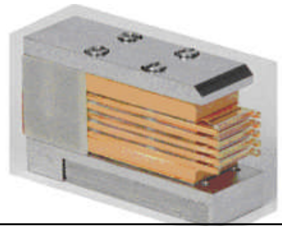
Super-efficient 480W stack

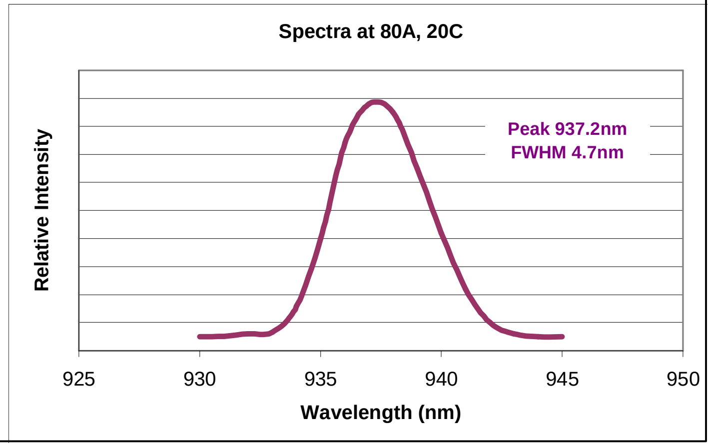
Stack Serial #: A668

Current (A)	Voltage (V)	Corr. Power (W)	E-to-O Eff.
6		0	
10	8.310	27	32.5%
20	8.480	96	56.6%
30	8.630	167	64.5%
40	8.750	233	66.6%
50	8.870	297	67.0%
60	8.980	367	68.1%
70	9.080	431	67.8%
77	9.155	480	68.1%
80	9.170	498	67.9%

Water Temp	~20C
Ith (A)	6.0
Eff per Bar (W/A)	1.11
I at 480W	77
V at 480W	9.16
Peak PCE	68.1%
Peak Wav (nm)	937.2





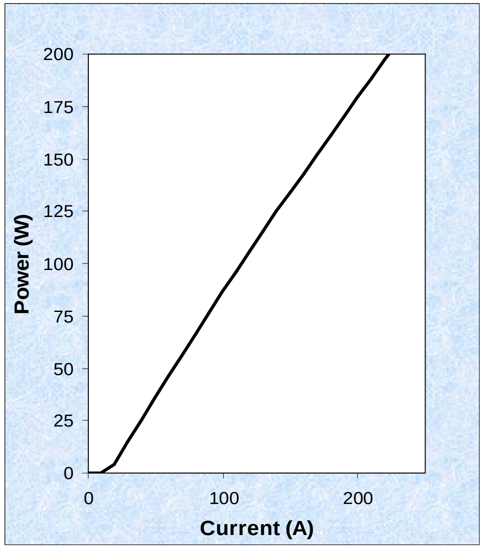


Power conversion efficiency (PCE) of >68% with good FWHM in 20°C water-cooled six bar stack

9xxnm 120W Bar Performance

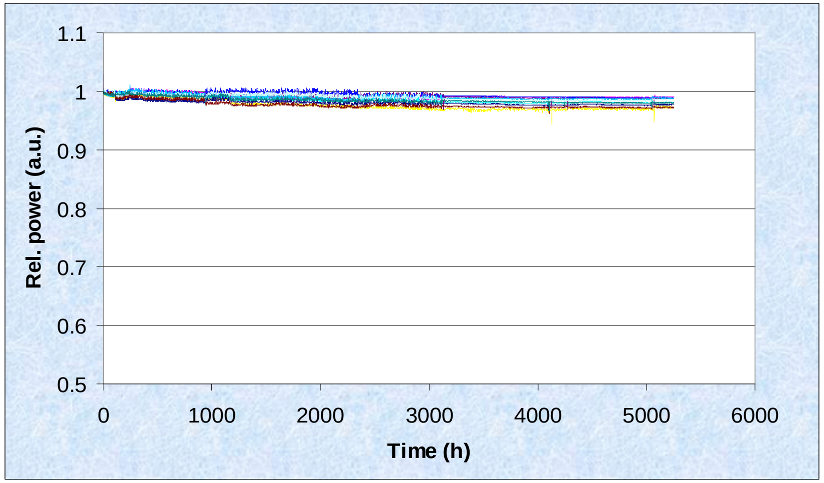
- Electro-Optical
  - Power: 120W @ 140A
  - Threshold: 14A
  - Slope Eff.: 1W/A

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



- 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

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



Pump power injection
Bar stacks vs single emitters

Stacks

- Open package
- Free space optic combiner
  - Opto-mechanical precision
- High heat density
  - MCC coolers with high water flow velocity
  - Bar needs to be solderred to MCC
  - Water and bar at same voltage potential. Bars and MCC in series
- Reliability
  - MCC limits lifetime (degradation by flow-erosion and electro-erosion)
  - MCC has different cte than bar. Strain
- **Need**
  1. **Ultra high efficient bar to reduce heatload**
  2. **Macro Channel coolers which are cte matched and galvanically isolated**
  3. **Optomechanical precision at low cost**

Single pigtailed emitters

- Hermetically sealed package
- Fiber combiners
  - Fiber combiner: Cost and reliability
- Distributed heat
  - Robust water coolers
  - Galvanic isolation
- Built on telecom technology
- **Need**
  1. **Ultra high brightness chip to increase power per pigtailed package**
  2. **Ultra high efficient chip to reduce heatload**
  3. **Fiberoptics and fiber combiners which are matched to pump diode**

Fiber Laser Reliability

Pump Diode reliability

- Chip: Methodology known from telecom
  - FMEA, Multi-cell testing
  - Apply to drive up power levels from single emitters
- Package
  - Single emitters: Known from telecom
  - Bar stacks: Opto-mechanics and cooling system:
  - Need to bring in FMEA and multi cell/damage limit testing methodology for stacks

Fiber

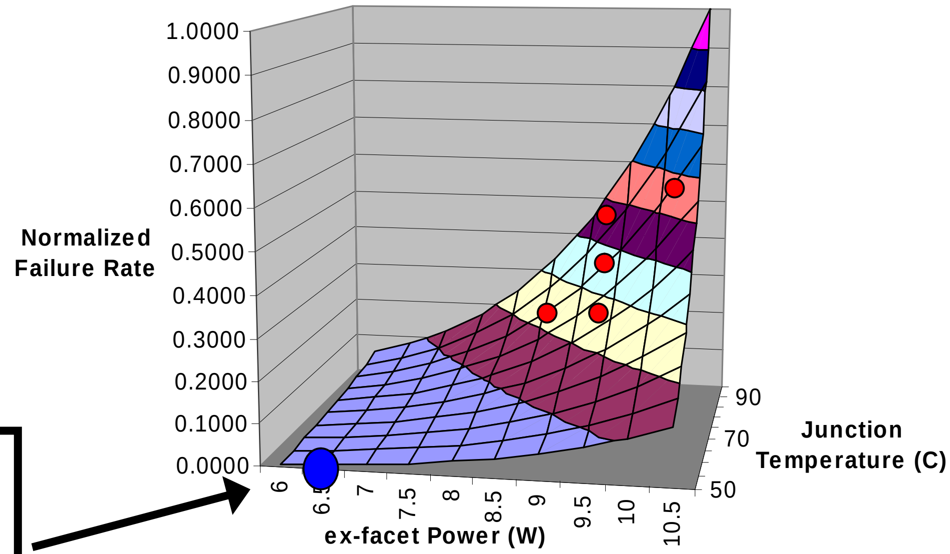
- Passive fiber:
  - Well understood from telecom
- Active fiber:
  - Photodarkening at high power operation. Understood by some manufacturers
- Fiber combiners
  - Need to increase power capability together with single emitters

Fiber Laser System

- Need to control fiber laser system aspects

What is a multi-cell test?

- Parallel lifetests varying key parameters:
  - Temperature
  - Optical Power and/or
  - Drive Current



Example for multicell test design

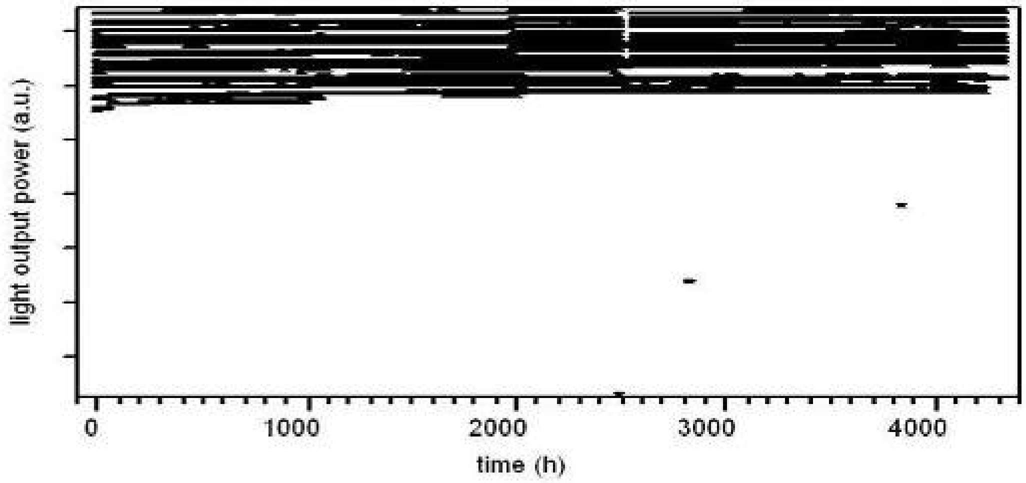
●	Multi-cell test conditions
●	Intended deployment conditio

- Reliable InAlGaAs lasers follow:

$$F(T_j, P, I) = F_{op} \bullet \exp\left(-\frac{E_A}{k_B}\left(\frac{1}{T_j} - \frac{1}{T_{op}}\right)\right) \bullet \left(\frac{P}{P_{op}}\right)^n \bullet \left(\frac{I}{I_{op}}\right)^m$$

→ (F_{op}, E_A, m, n) determined from best fit of multi-cell data

SES8-9xx-01: Reliability assessment



I_{op}= 9 A,
P_{op}~ 8.2 W,
T_{jct} ~ 111°C

Multi-Cell test

- **I_{op}: 9 A -13 A (Pout: 8 W- 11 W)**
- **T_{jct}: 100°C -140°C**

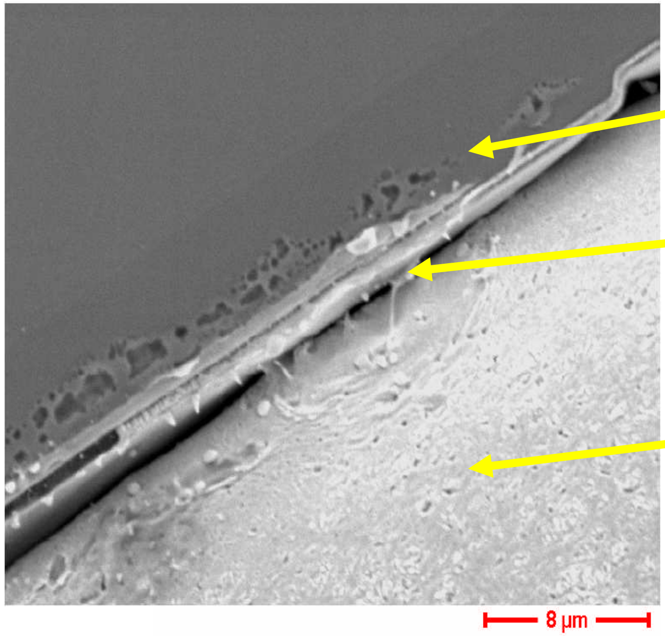
Acceleration model:

- **FR ~ I^xP^y exp($-E_a/k_bT$), x = 0, y = 5, Ea = 0.45 eV**

Reliability

- **< 3 kFIT @ 8.2 W, 25 °C (heat sink temperature)**

Fiber Laser Reliability System



2005, A. Jakubowicz, Bookham

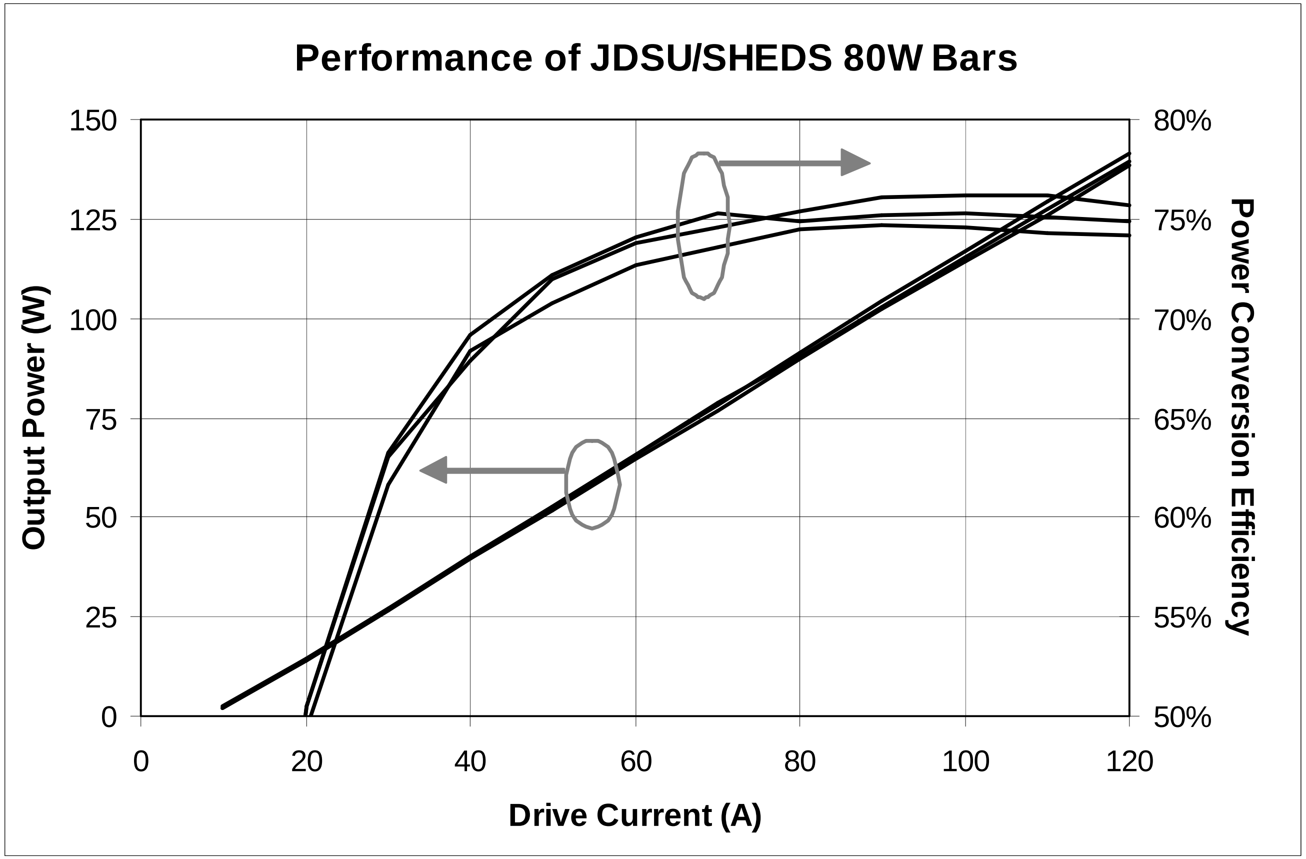
- Damaged broad area pump chip by optical back-travelling pulse in fiber amplifier (Er)
- Add protection by isolators?

Outlook

- MOPA arrangement
  - Diode seed lasers are easily modulated
  - Cascade of fiber power amplifiers for easy power scalability
- 940/960nm and 920nm bands have robust pump diodes
  - 976nm is very challenging from wavelength stability requirement
- Reliability has to include diodes, fiber and system
  - for higher power chips: Methodology kown
  - For higher power active fibers: Need methodology (and more manufacturers)
  - Reliability trade-offs of system needed to optimize fiber laser costs
- Pump diode cost reduction through
  - Evolution (takes time)
  - Inventions
    - Pigtailed single emitters optimally matched to fiber system
    - Stacks on galvanically isolated, expansion matched macro channel coolers
  - High volume by a few lead suppliers

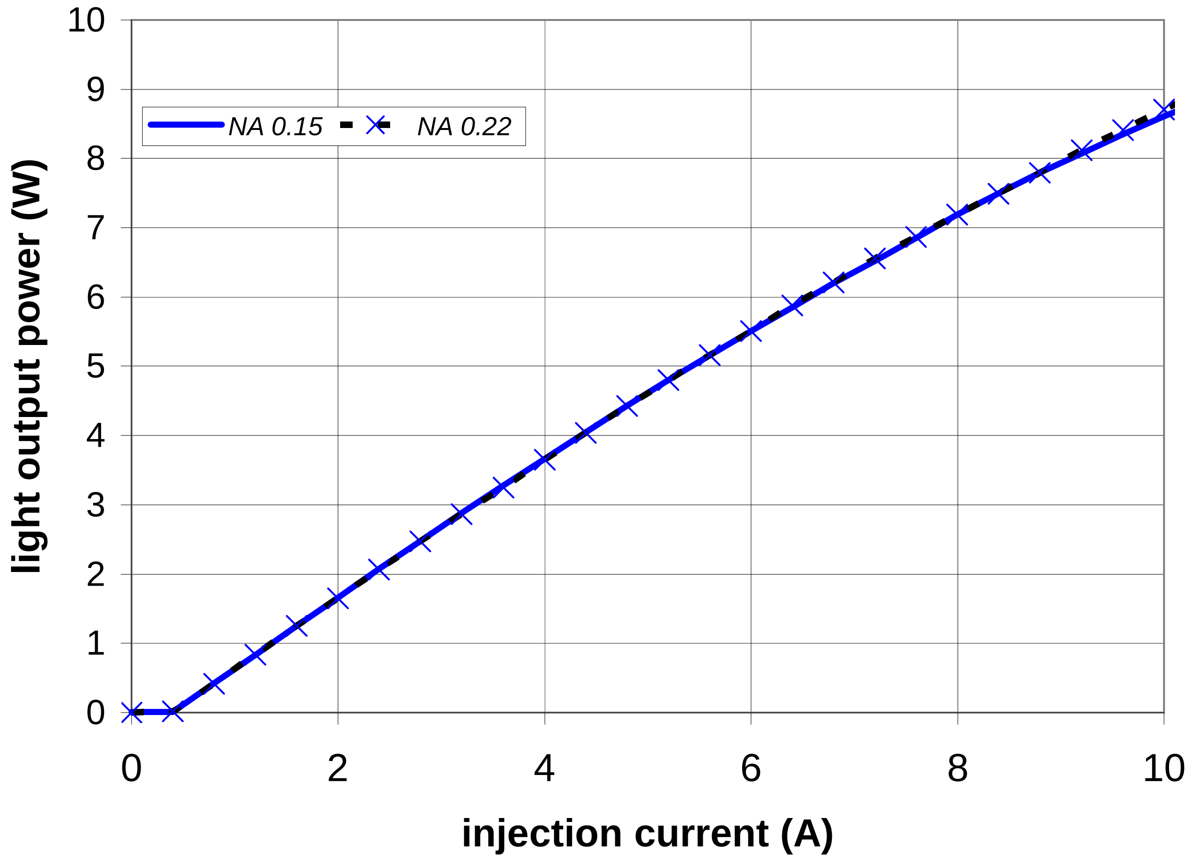
Addendum

Super–efficient 80W 940nm bar



Power conversion efficiency (PCE) of >75% in 80W, 20°C water-cooled 1cm 940nm bars

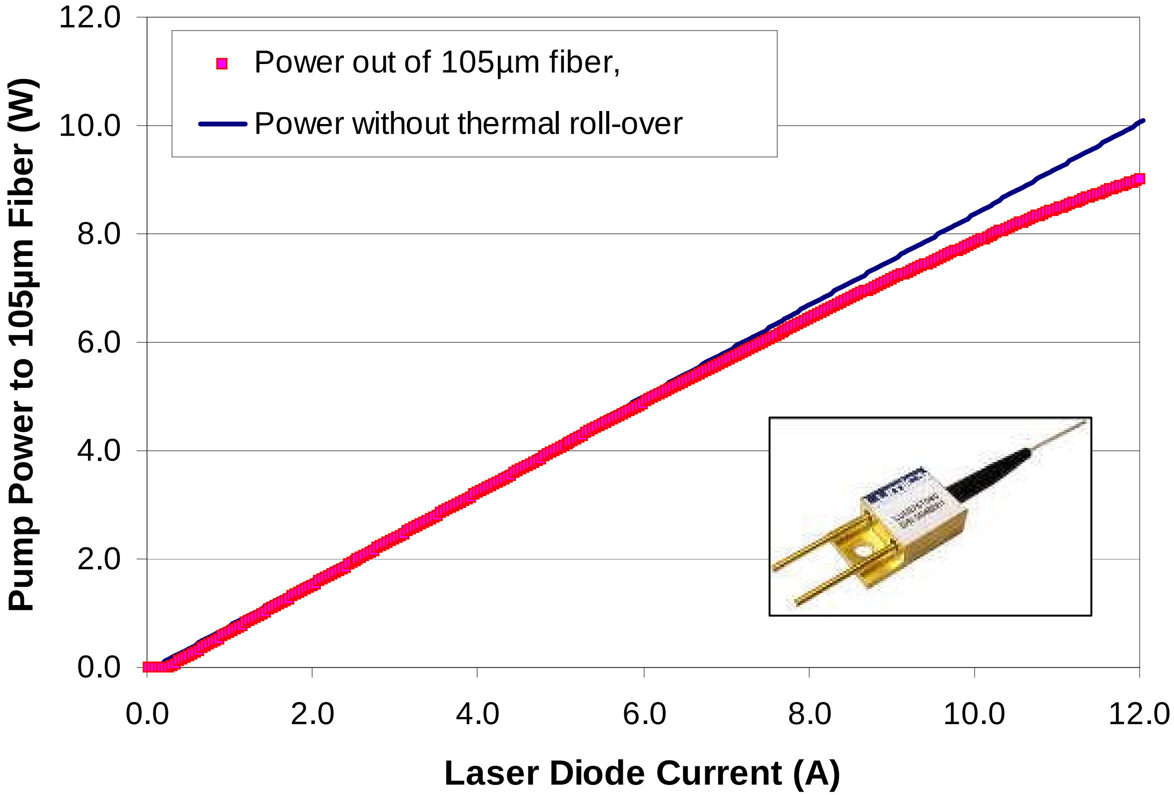
MU7-9xx-01: NA 0.15 vs. NA 0.22



- Same performance for NA 0.15 and for NA 0.22 MM fiber.

915nm pump laser

Lumics
Devices for Optical Systems



Optical output power (ex-fiber) versus current for the 915nm TO-220 module
Currently Lumics sells 4W versions of 808, 915 and 975nm
7W is announced for Q3 2006

9xx Laser Diode Bars

915nm 940nm 980nm	Bar on MCC	Bar on MCC Base&Cover	Vertical Bar on MCC Stack	MM Bar on Cu Block
50%FF	**80W** BAC80C-9xx-01	**80W** BAC80C-9xx-02		
50%FF	**120W** BAC120C-9xx-01	**120W** BAC120C-9xx-02	**2400W** VBA2400C-9xx-01	
30%FF	**50W** BAC50C-9xx-01	**50W** BAC50C-9xx-02		**50W** BPC50C-9xx-01
20%FF	**50W** BAC50C-9xx-03	**50W** BAC50C-9xx-04		**50W** BPC50C-9xx-02