The Changing Technology of Solid State Lasers

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Introduction

- “Fiber” and “solid state” or “bulk” lasers have been treated as separate categories, likely because of the nearly exclusive application of fiber lasers to the telecom enterprise
- Non-telecom fiber lasers are clearly emerging as an important technology
- The field of solid state lasers should really include fiber lasers (ASSP 2004 adopted this position)
- This talk attempts to cover both and (I hope) provide useful information to both fiber and bulk laser investigators and developers

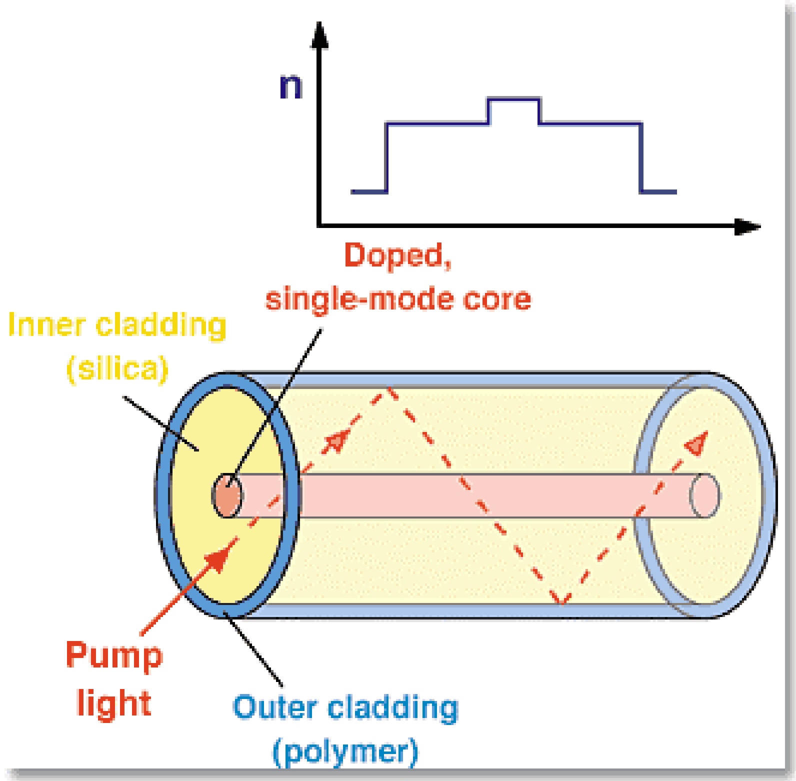
Outline

- Quick review of fiber-laser designs
- Diode pump lasers for bulk and fiber lasers
- The battle for cw power
- The changing boundaries of short-pulse lasers
- Driving nonlinear optics
- Fiber and bulk lasers working together
- Future directions - photonic fibers
- Summary

Will be available at www.qpeak.com/Research/recent_technical_papers.htm

Quick review of fiber-laser designs

Cladding-pumped fiber laser allows multimode pumping of single-mode cores

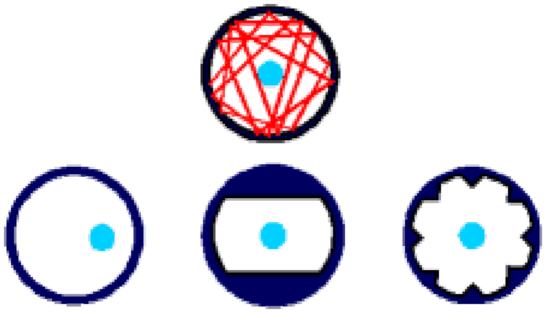


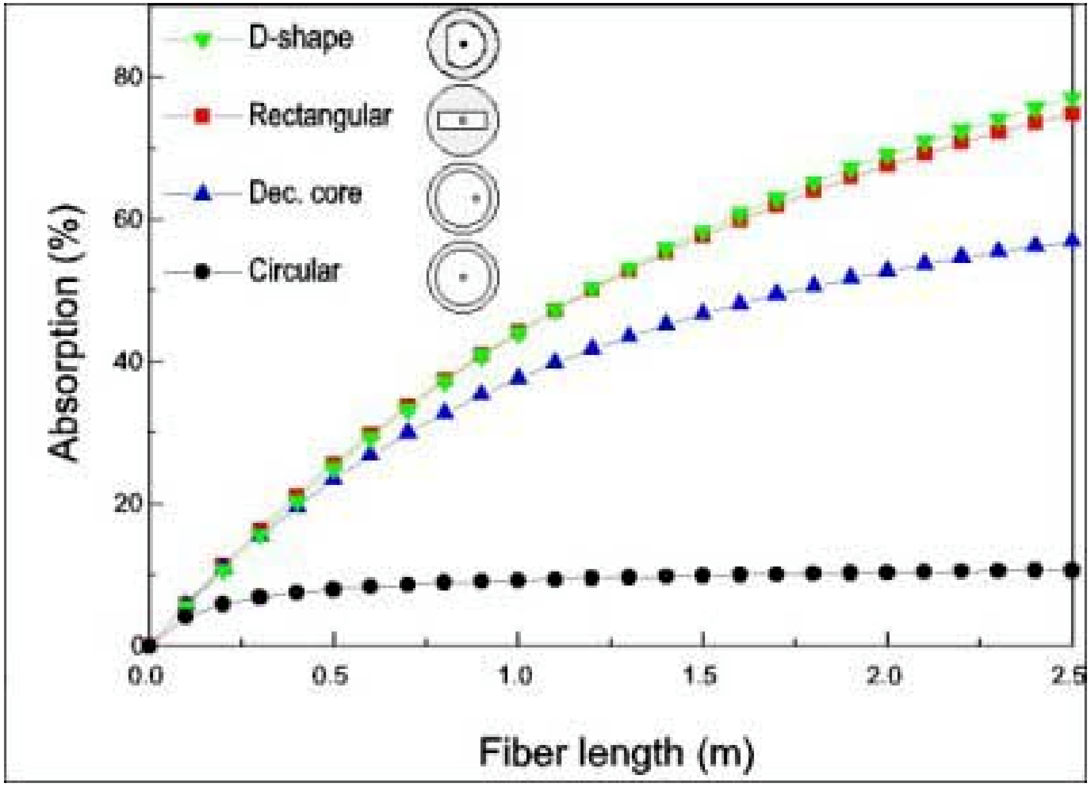
Elias Snitzer first described cladding pumped lasers in 1988

Maurer, U.S Patent 3,808,549 (April 30, 1974)

J. Kafka, U.S. Patent 4,829,529 (May 9, 1989)

Non-circularly symmetric cladding geometries permit effective overlap with laser core

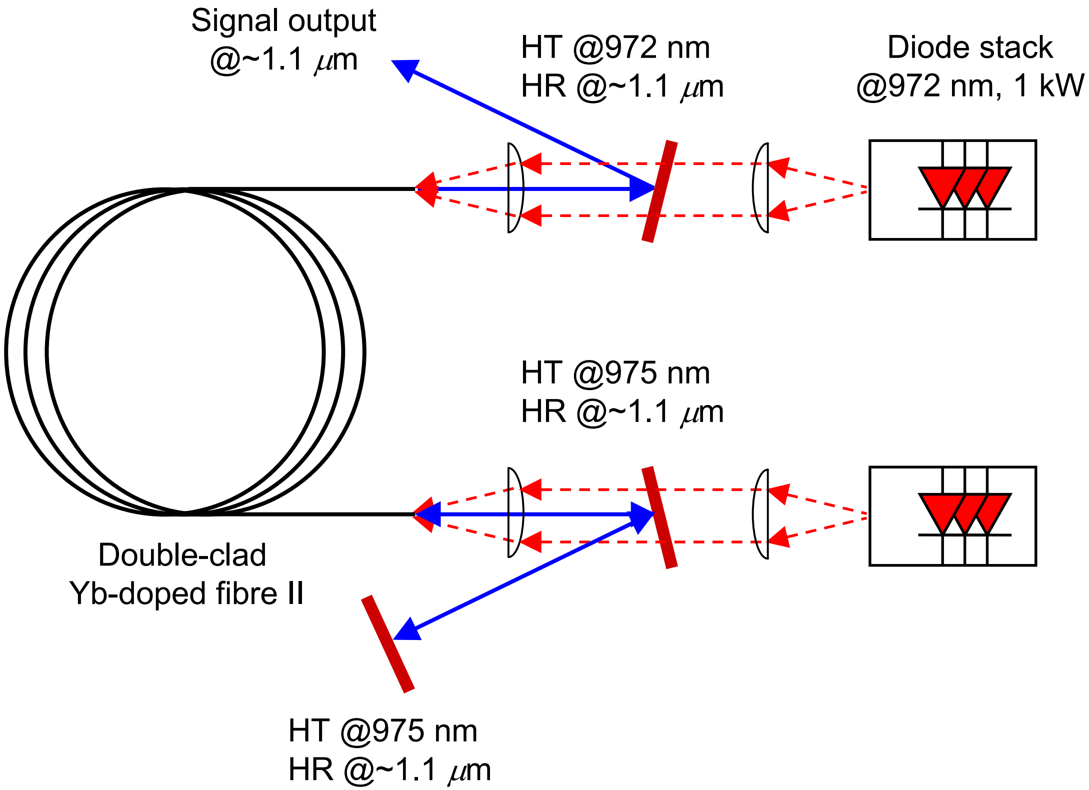




http://www.iap.uni-jena.de/fawl/rdtfawl.html

Absorption length is increased by the ratio of cladding to core areas

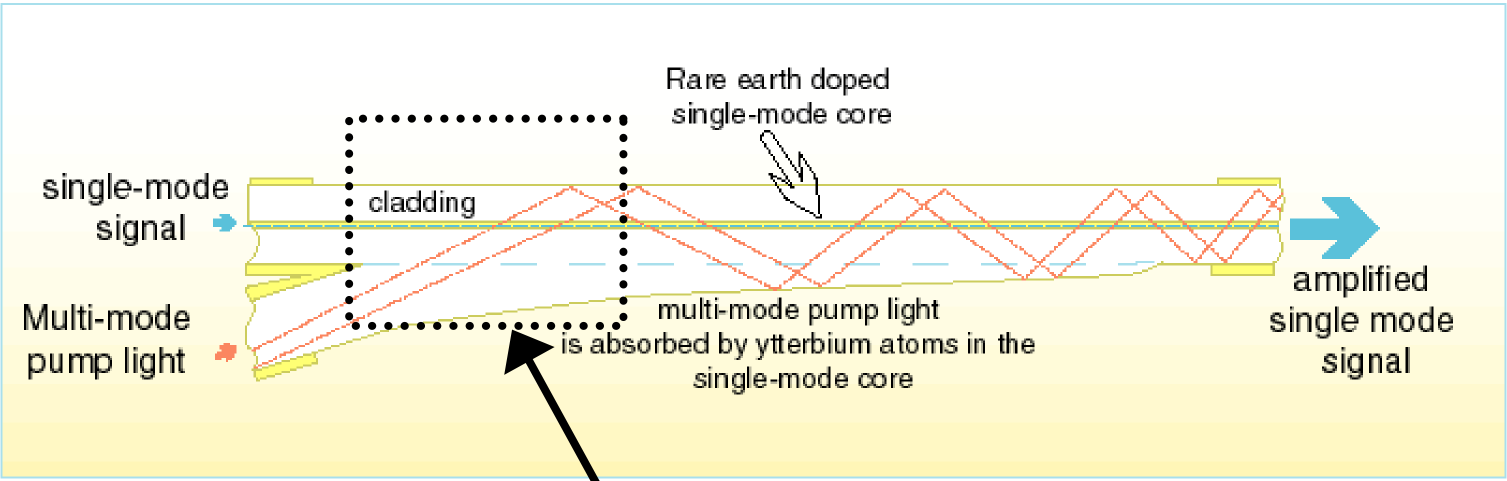
End-pumped double-clad requires dichroic mirrors and “bright” pump source



Ytterbium-doped large-core fiber laser with 1 kW continuous-wave output power

Y. Jeong, J.K. Sahu, D. N. Payne, and J. Nilsson, ASSP 2004

Multi-Mode Coupler Approach - IPG Photonics

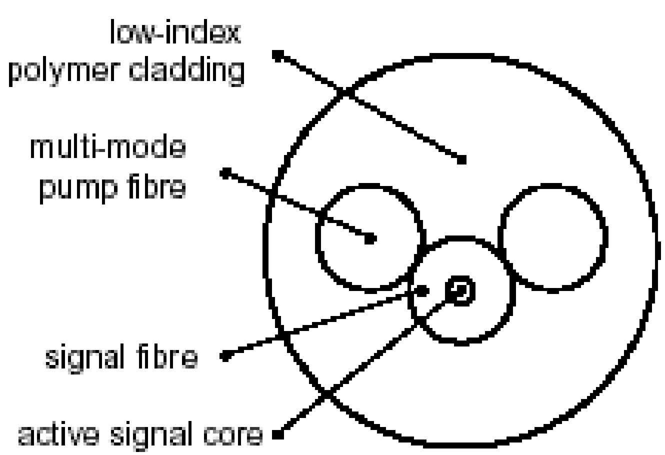


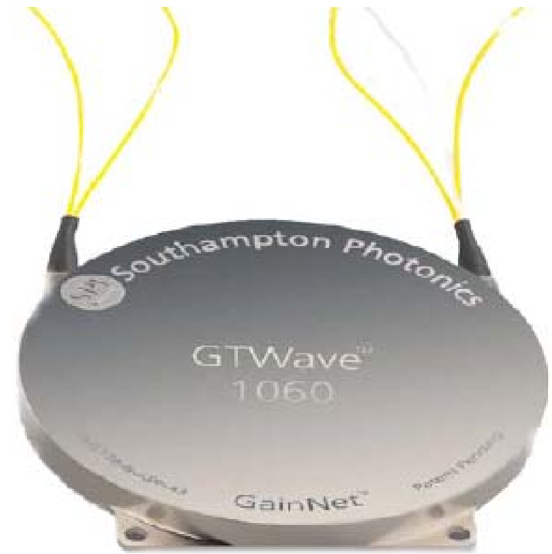
Multi-Mode Coupler Region

- **Multi-Mode coupler is created by fusing under high temperature conditions double-clad doped fiber with multi-mode fiber from pump source**

Qpeak APPLIED PHOTONIC SYSTEMS

SPI has GTWave Technology





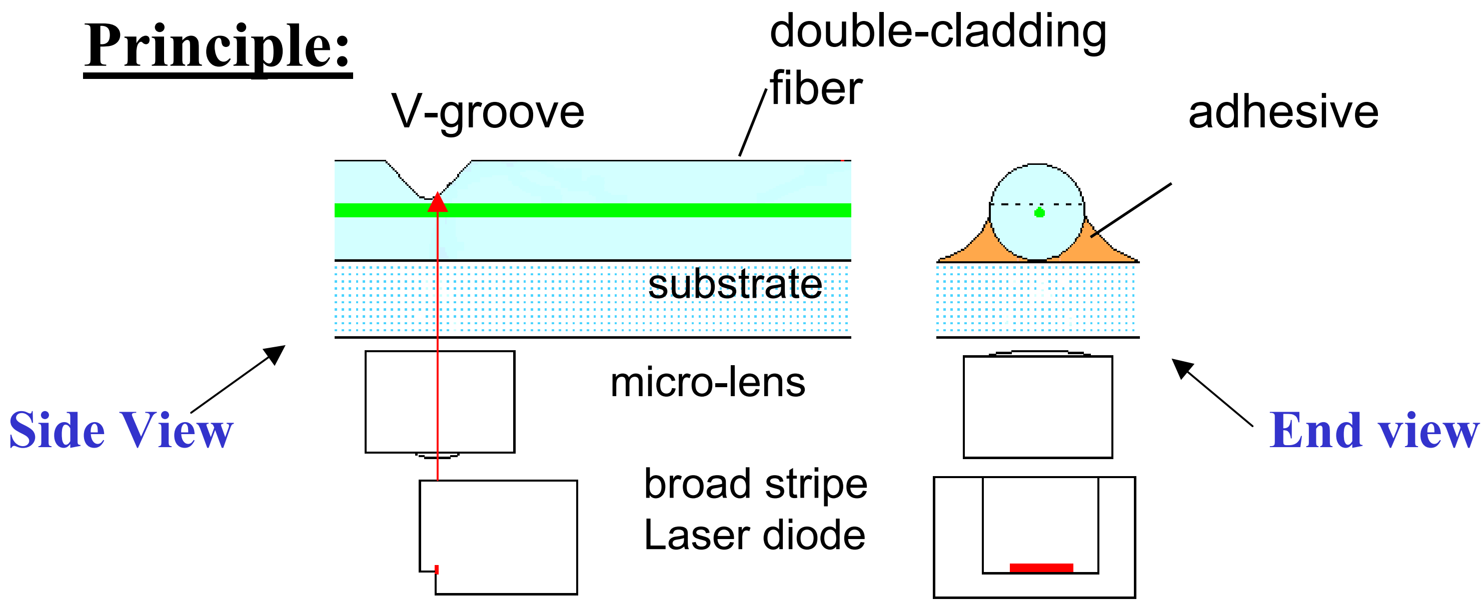
> 70 W per module

Qpeak APPLIED PHOTONIC SYSTEMS

V-Groove Side Pumping: Keopsys

VSP Technology TM

Principle:

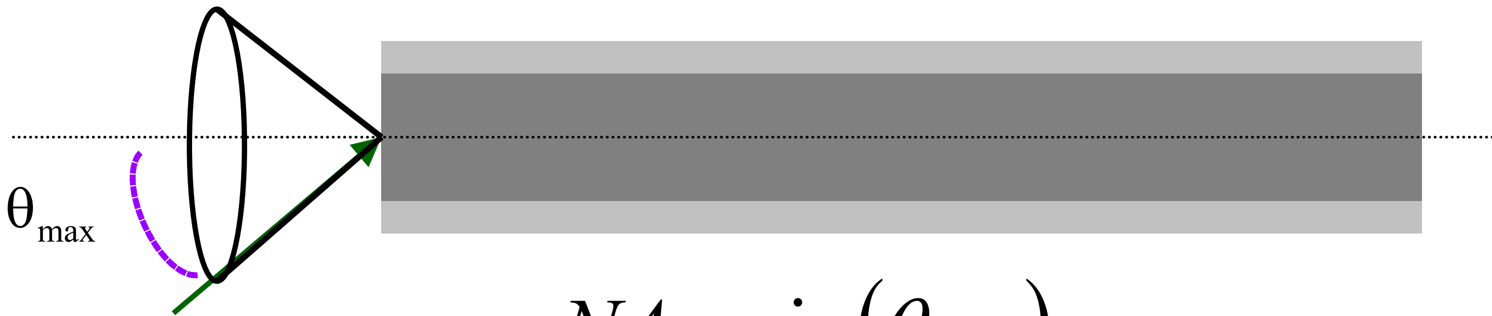


- **High efficiency coupling (>90%) with broad area inexpensive laser diodes & multiple V-grooves**
- **Simple & compact packaging, with large alignment tolerances**
- **No loss of light in core and no need for multiplexer**

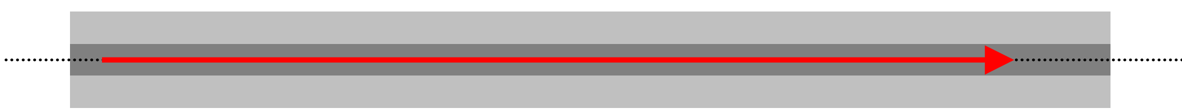
Beyond double-clad designs, further strategies are needed for fiber-laser power scaling

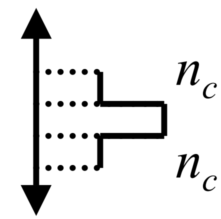
- **Eventually, the small area of the mode in the core creates limits:**
  - **Optical damage to the fiber faces (more later)**
  - **Bulk damage at flaws or defects**
  - **Nonlinear optical effects in the bulk of the fiber**
- **Nonlinear effects include:**
  - **Stimulated Brillouin scattering for single-frequency sources, cw or pulsed > 10 ns**
    - Adds frequency components and can lead to backward wave generation and catastrophic pulse shortening
    - Threshold follows (Core area)/(Fiber length)
  - **Stimulated Raman scattering**
    - Adds frequency components, may limit NL conversion
    - Threshold follows (Core area)/(Fiber length)
  - **Self phase modulation**
- **Larger core/mode size is desirable – lower intensity *and* shorter fiber length for double-clad designs**

Step index fiber - limits for single mode



$$NA = \sin(\theta_{max})$$





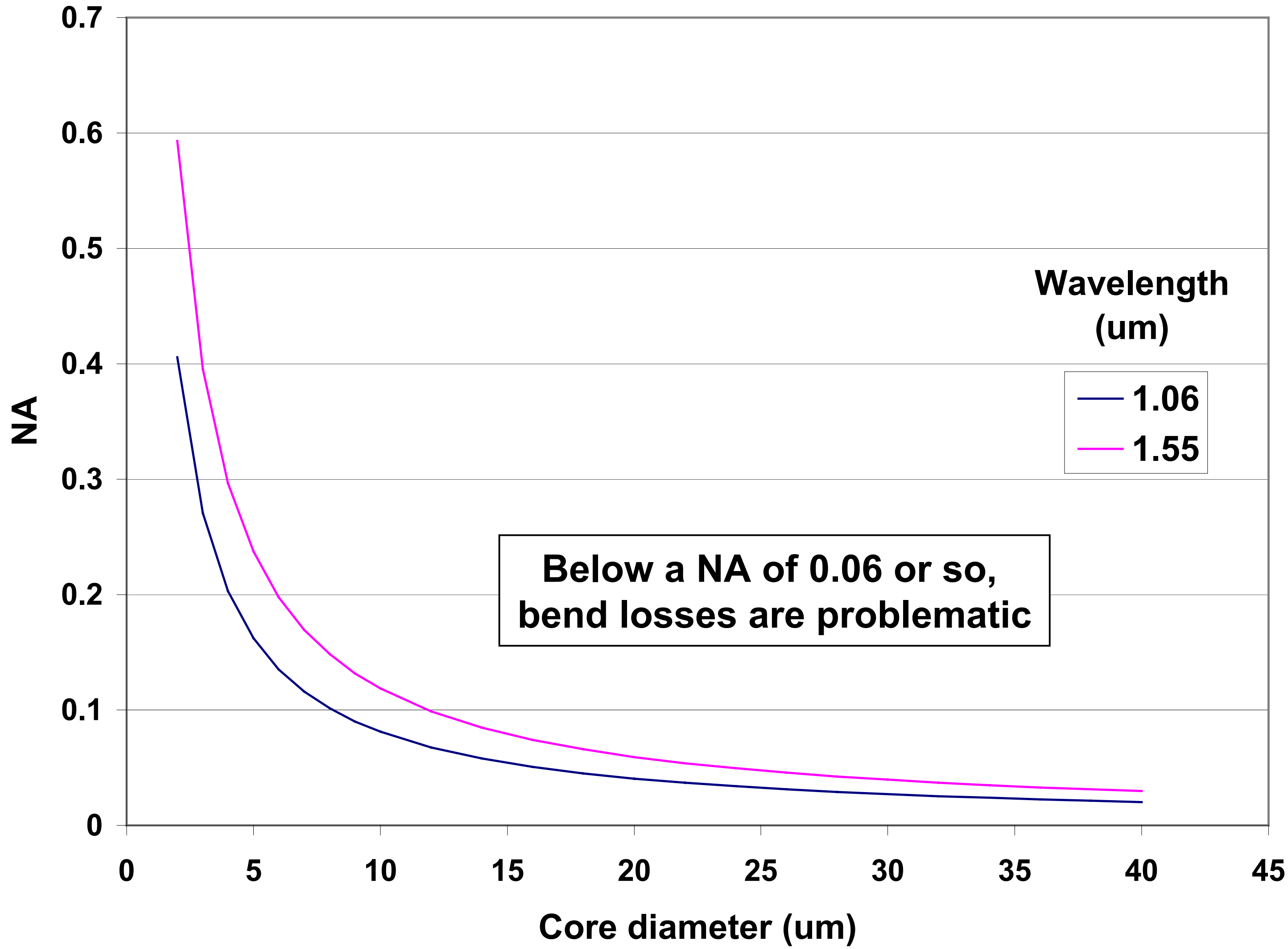
$$NA_{step} = \sqrt{n_f^{\,2} - n_c^{\,2}}$$

$$V = 2\pi \frac{a}{\lambda_o} NA$$

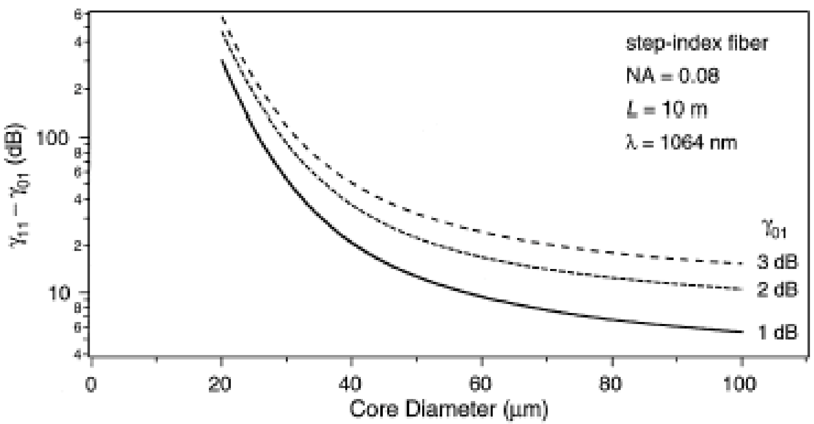
a is core radius, λ is wavelength

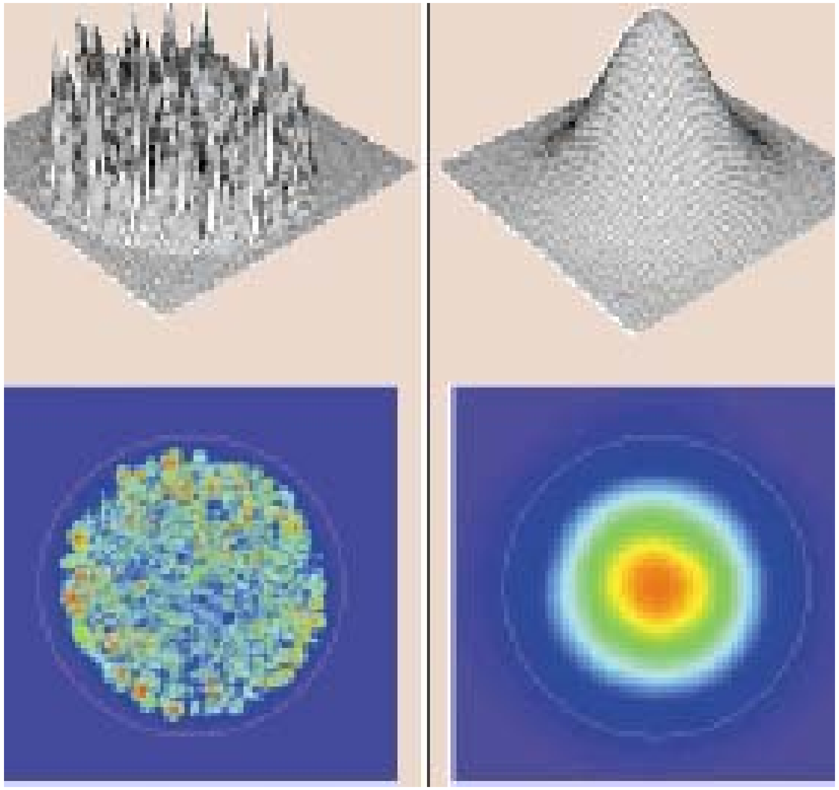
V < 2.405 for single-mode fiber

Relation of core diameter to NA for single-mode step-index fiber



Coiling fiber allows single-mode with V > 2.4

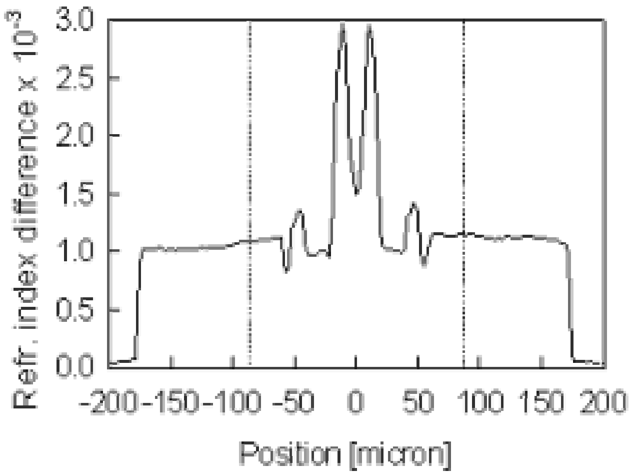




25 um core diameter, NA 0.1 (V=7.4 at 1064 nm)
Straight (left) 1.58 cm coil dia. (right)

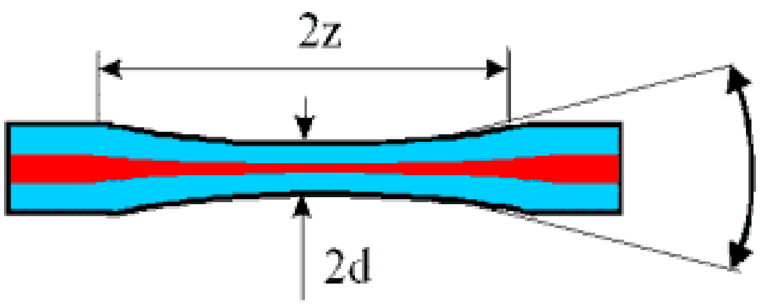
J. Koplow, D. Kliner and L. Goldberg, Optics Lett. 25, 442 (2000).

Other tricks around the core size limits



Complex index profiles
(also good for wavelength discrimination)

J.A. Alvarez-Chavez *et al*.,
Opt. Lett 25, 37 (2000).



Tapered sections

http://www.orc.soton.ac.uk/hpfl/tapers.php

Careful launching of low-temporal coherence,
single-mode beam into high-quality, thick cladding, multimode fiber
M.E. Fermann, Opt. Lett. 23, 52 (1998).

Or, Photonic Crystal Fibers (PCF) - more later

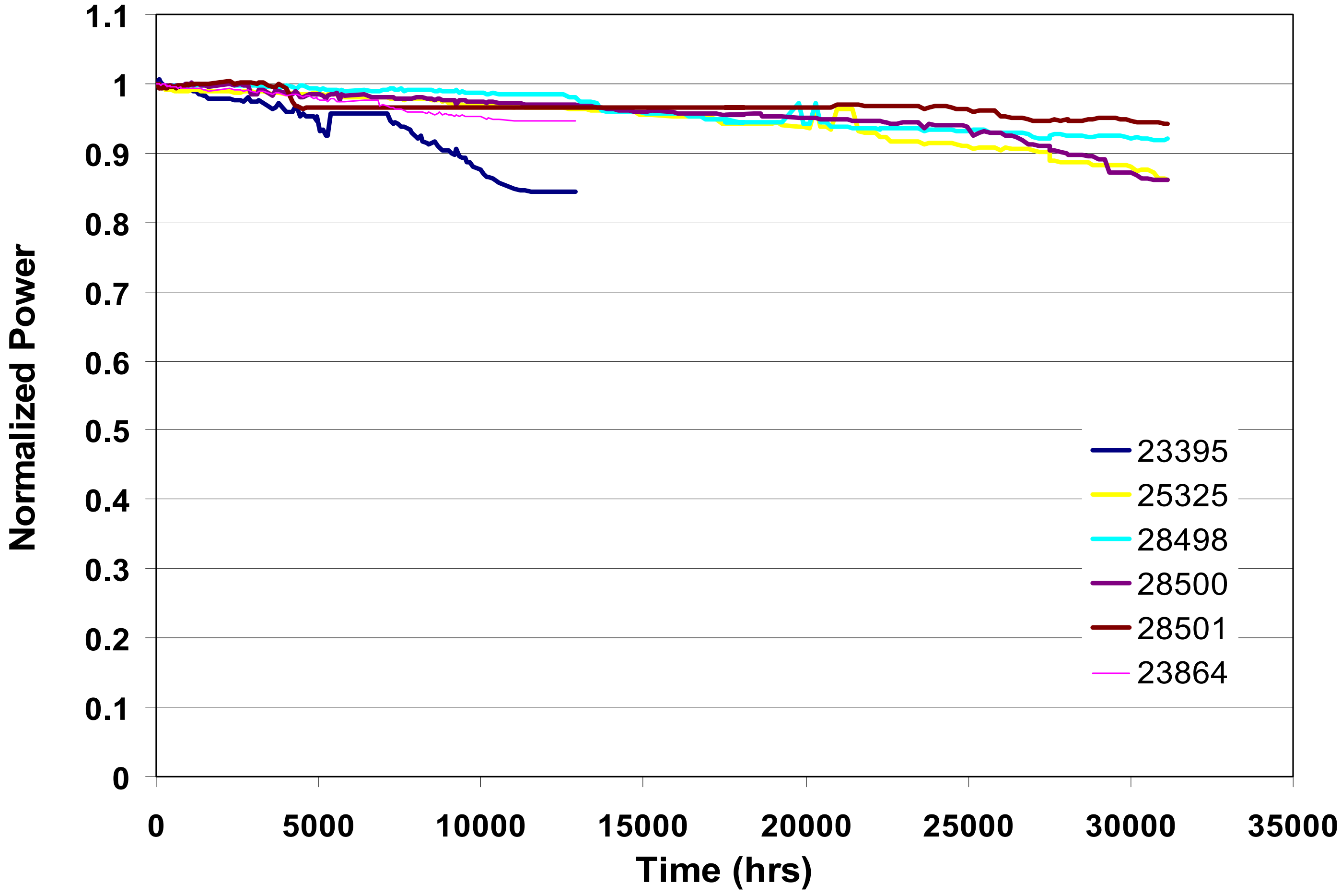
Diode pump lasers for bulk and fiber lasers

Q-peak APPLIED PHOTONIC SYSTEMS

JDSU 5-W 915-nm diode laser
Telcordia-qualified, long-lifetime pump

JDS Uniphase's ultra-reliable 6390 series laser diodes offer 5 W of laser power from a 100 µm fiber into 0.2 NA. The L3 package is a redesign of the existing fiber-coupled L2 package, incorporating telecom design approaches into a commercial product and resulting in a reliability of >200,000 hours MTBF.

Coherent 808nm 30W FAP-B
MTTF: 47000hrs(90%CL)



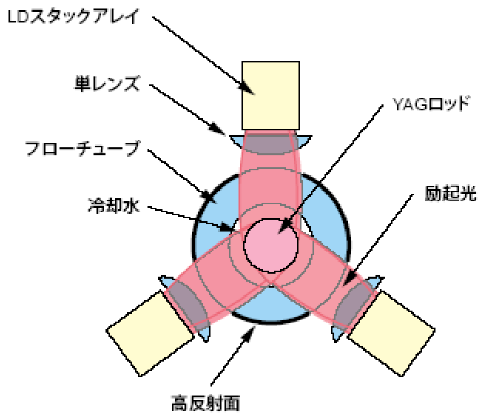
Q-peak APPLIED PHOTONIC SYSTEMS

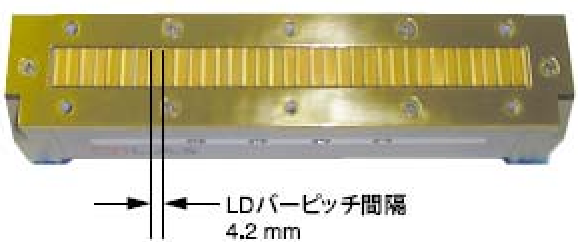
High-brightness pump sources

- Apollo Instruments fiber-coupled diode lasers (0.22 NA):
  - 35 W from 100 um
  - 150 W from 200 um
  - 400 W from 400 um
  - 500 W from 600 um, 0.22 NA fiber
- Laserlines stacked, beam-shaped bars
  - 500 W, 40x50 mrad
  - 1000 W, 60x80 mrad
  - 6000 W, 85x400 mrad
- Nuvonyx stacked, beam-shaped bars
  - 4000W, focusable to 12.5 x 0.5 mm spot

The battle for cw power

Toshiba and Shibaura diode-pumped Nd:YAG rod lasers





"Toshiba succeeded in obtaining an output power of 12 kW with an efficiency of 23 %, which are, to our knowledge, the highest values for a Nd:YAG laser."

Shibaura LAL-210/220/230/240/260 SERIES 4.5 kW with 600 um fiber

Average power thermal limits

Evaluated by Brown and Hoffman, IEEE JQE 37, 207 (2001)

For 9.2-um core, 600 um fiber diameter

34 kW/m of heat generation leads to fracture

48 W/m of heating leads to silica melting in center for static air cooling

but 100 W/m of heating demonstrated in practice without problems (Y. Jeong, Southampton, LEOS 2003 Annual)

Heat generation in YDFLs ~15% of output power: 150 W/kW

$\rightarrow$ ~1 kW/m optical power generation in efficient YDFLs

Limit to power is not fracture or index gradient but "core meltdown"

Future systems may use water cooling to increase power/length

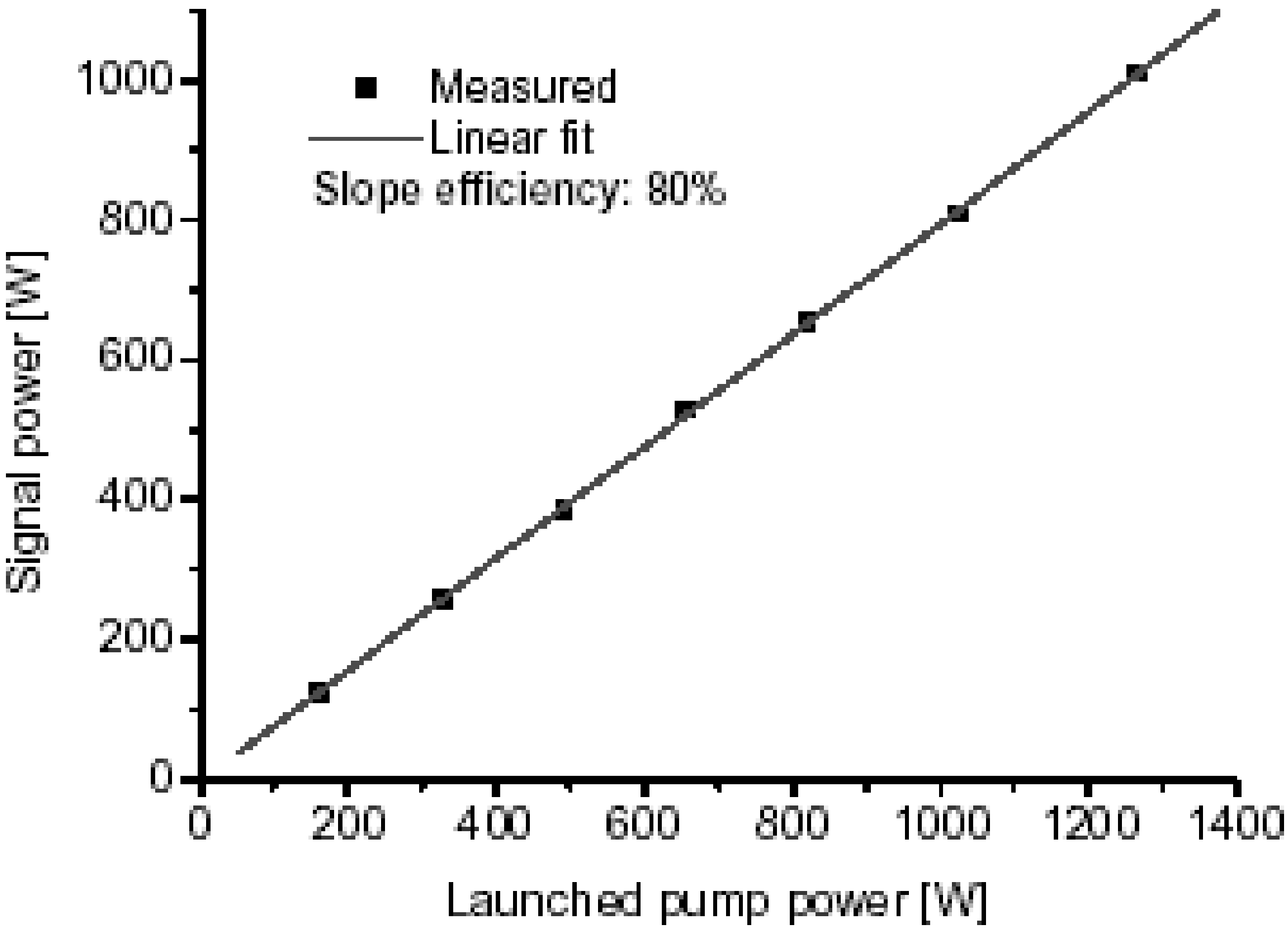
High-power cw fiber laser results

Group	Power (W)	Lambda (nm)	M^2	Core (um)	NA	L (m)	Pump (W)	Notes
SORC	610	1098	1.3	43	0.09	9	1000	
/SPI	1010	1096	3.4	43	0.09	8	1500	
	264	1060	<1.1	25	0.06	7	500	SF, pol.
	120	1565	1.9	30		4	325	
U. Mich.	155	Yb	1.32	30	0.06	25	475	Pol,coil
/Fraun.	700	1092	1.42	20	0.06		970	coil
NGST	155	1083	1.17				200	SF, pol.
IPG	300	Yb	<2					YLR-300
	700	Yb	<4					YLR-700
	250	1076	1.04	14			450	Pol.
Jena	310	Yb	1.1	20	0.07	45	400	Pol.
	1300	*1090*	*<3*	*38*	*0.06*	*50*	*2200*	*launched*

CLEO 2004 Session CMS

CLEO 2004 Postdeadline

SORC/SPI results for first >1 kW single-fiber laser

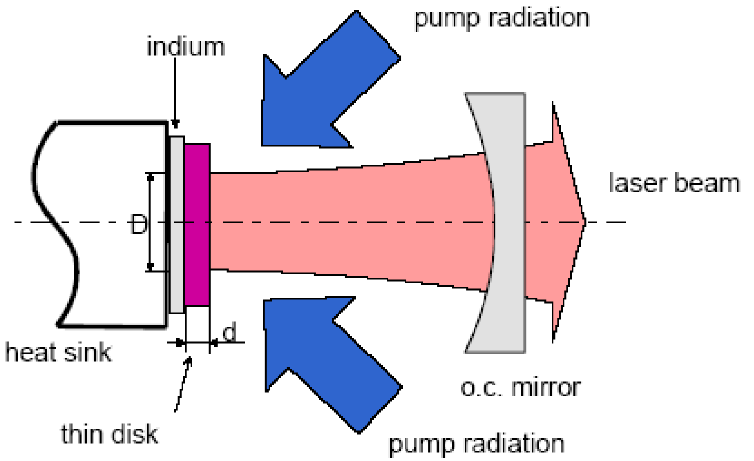


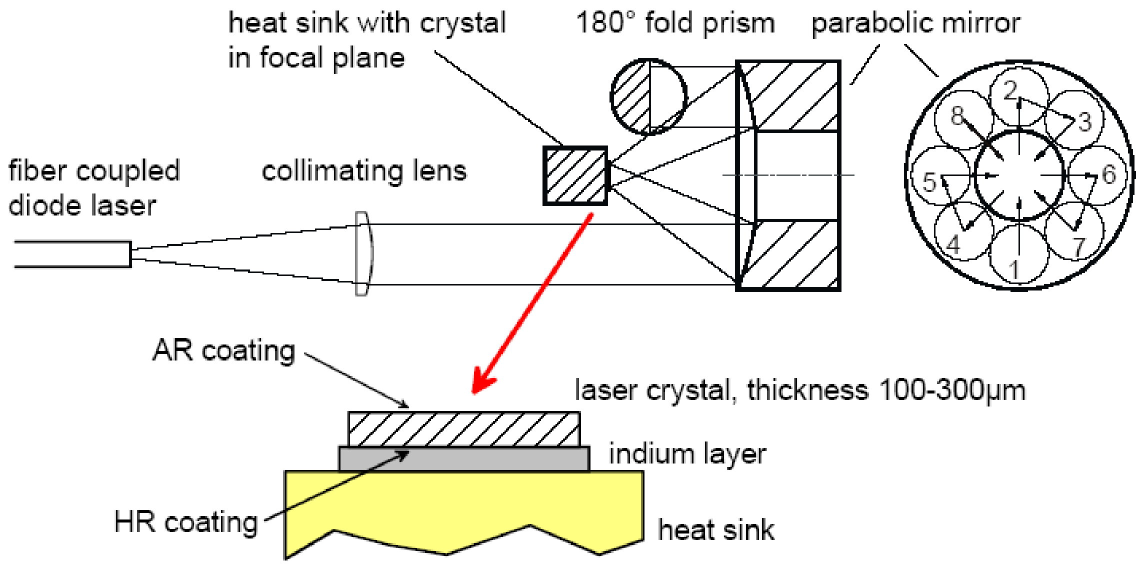
IPG Photonics YLR-HP Series:
1-10kWatt Ytterbium Fiber Lasers

- Up to 10 kW Output Optical Power
- Over 20% Wall-Plug Efficiency
- Excellent Beam Parameter Product
- >50,000 Hours Pump Diode Lifetime
- Air or Water Cooled Versions
- Maintenance Free Operation
- Up to 200 m Fiber Delivery
- 2 Year Warranty

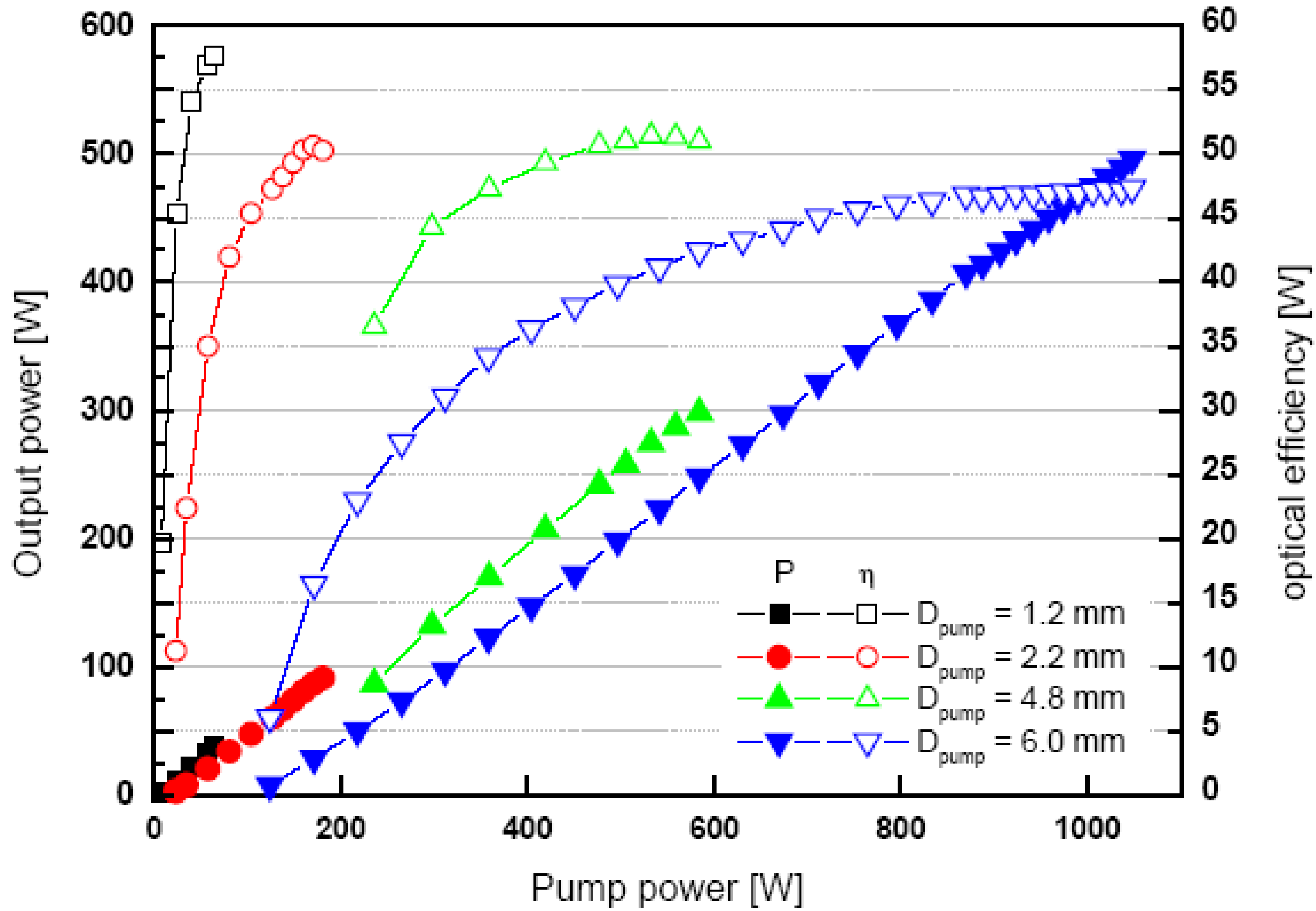
Latest performance, May 2004
5.5 kW, 4.3 mm-mrad, 100-um fiber delivery

New “bulk” laser technology: thin-disk lasers





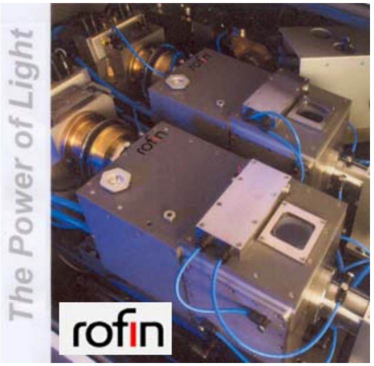
Single thin disk generates 500 W, 50% efficiency



A. Giesen "Thin disk lasers: recent results and future prospects"
SPRC Annual Meeting, September, 2003

Summary of thin disk results, late 2003

- Trumpf-Laser: 4 kW thin disk laser, M² < 20, η > 25%
- Jenoptik L.O.S.: Thin disk laser up to 8 W green (532 nm), 0,8 W blue (457 nm), 2 W red (660 nm) Q-switch thin disk laser
- ELS: Fundamental mode thin disk laser up to P > 100 W c.w., > 15 W green
- Rofin-Sinar 750 W, 1,5 kW, 3 kW thin disk laser

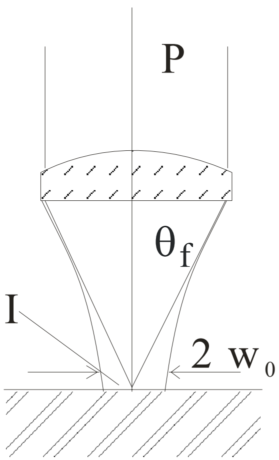


Data achieved in laboratory:

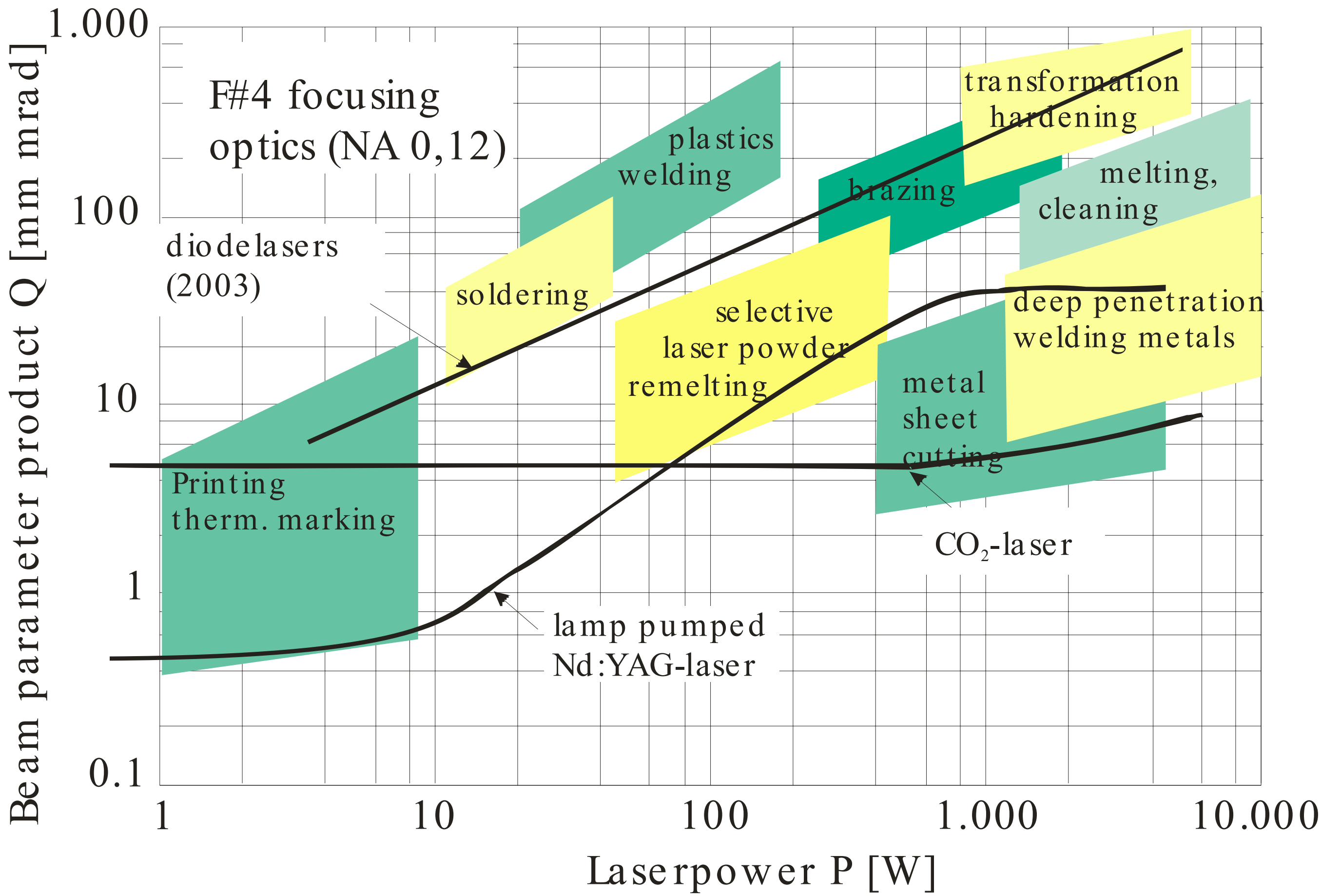
- Rofin-Sinar P > 1,5 kW out of one disk
- Trumpf-Laser P > 2 kW out of one disk

A. Giesen "Thin disk lasers: recent results and future prospects"
SPRC Annual Meeting, September, 2003

Laser parameters for materials processing



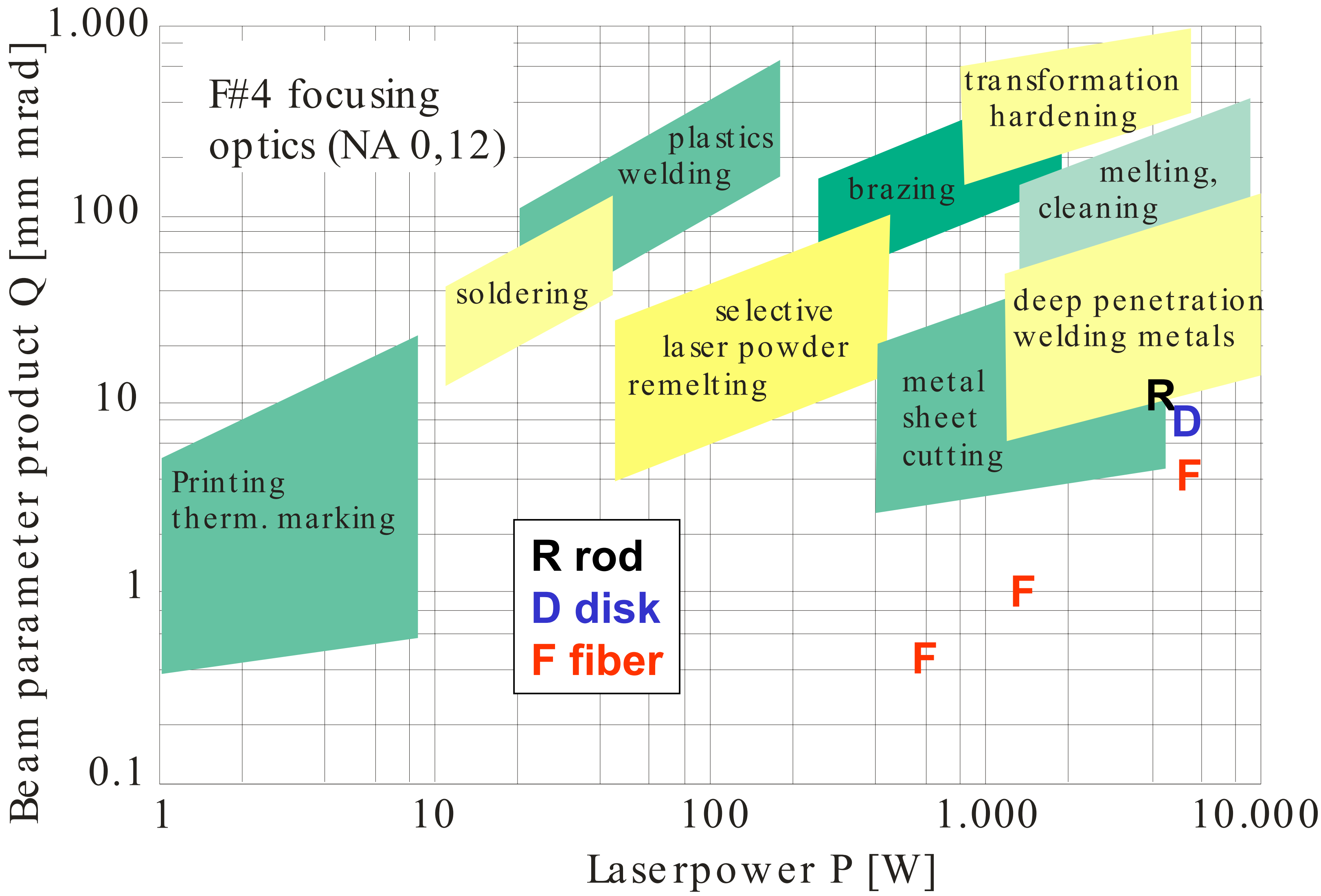
$$Q = \theta_f \cdot \sqrt{\frac{P}{I \cdot \pi}}$$



Fraunhofer Institut Lasertechnik

Courtesy Peter Loosen, ILT

Advanced diode-pumped solid state lasers applied to materials processing

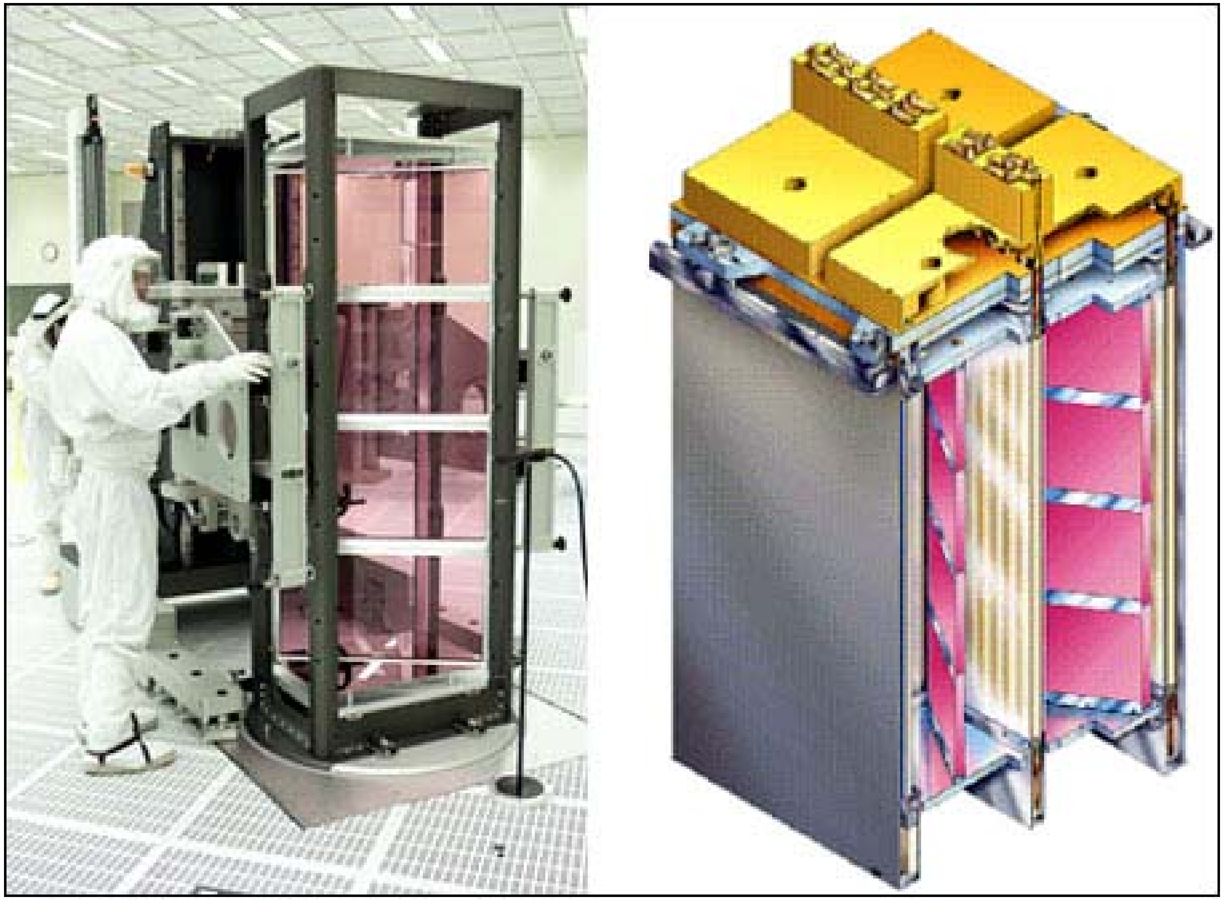


On to higher powers

- **Single-mode fibers to the 3 kW level?**
- **Fiber laser bundling can provide > 10 kW**
- **Phased arrays of fiber lasers**
- **But:**
  - **US High-Energy Laser Program (HEL JTO) funding two 25 kW bulk solid state laser demonstrations at Raytheon and TRW**

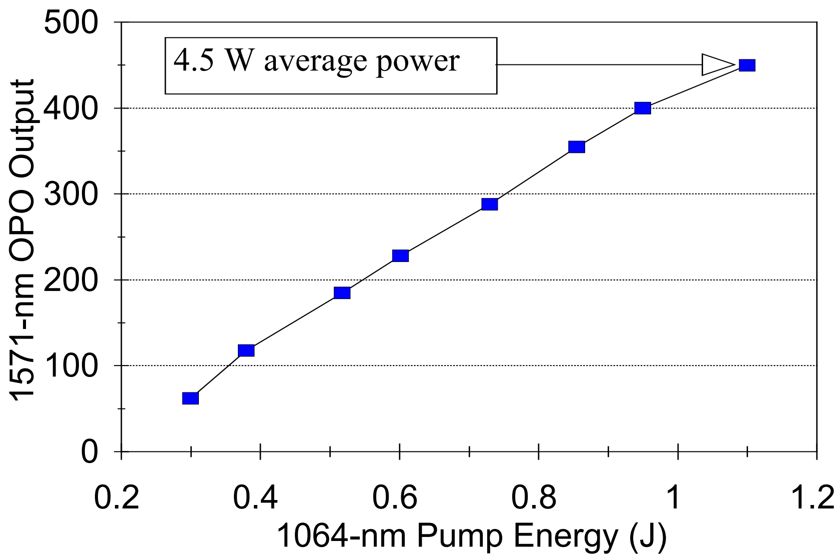
The changing boundaries of short-pulse lasers

Yb pulsed fiber lasers not ready for NIF

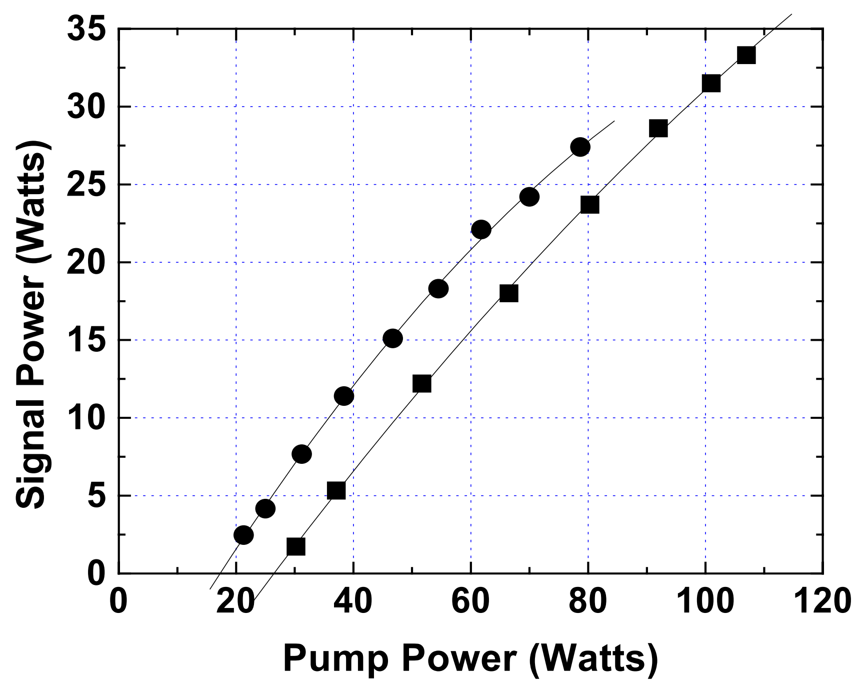


Glass Slab LRUs being prepared for transport from the Optics Assembly Building (OAB) into Laser Bay 2. The drawing on the right shows a cut-away view of a NIF amplifier with glass slabs and flashlamps

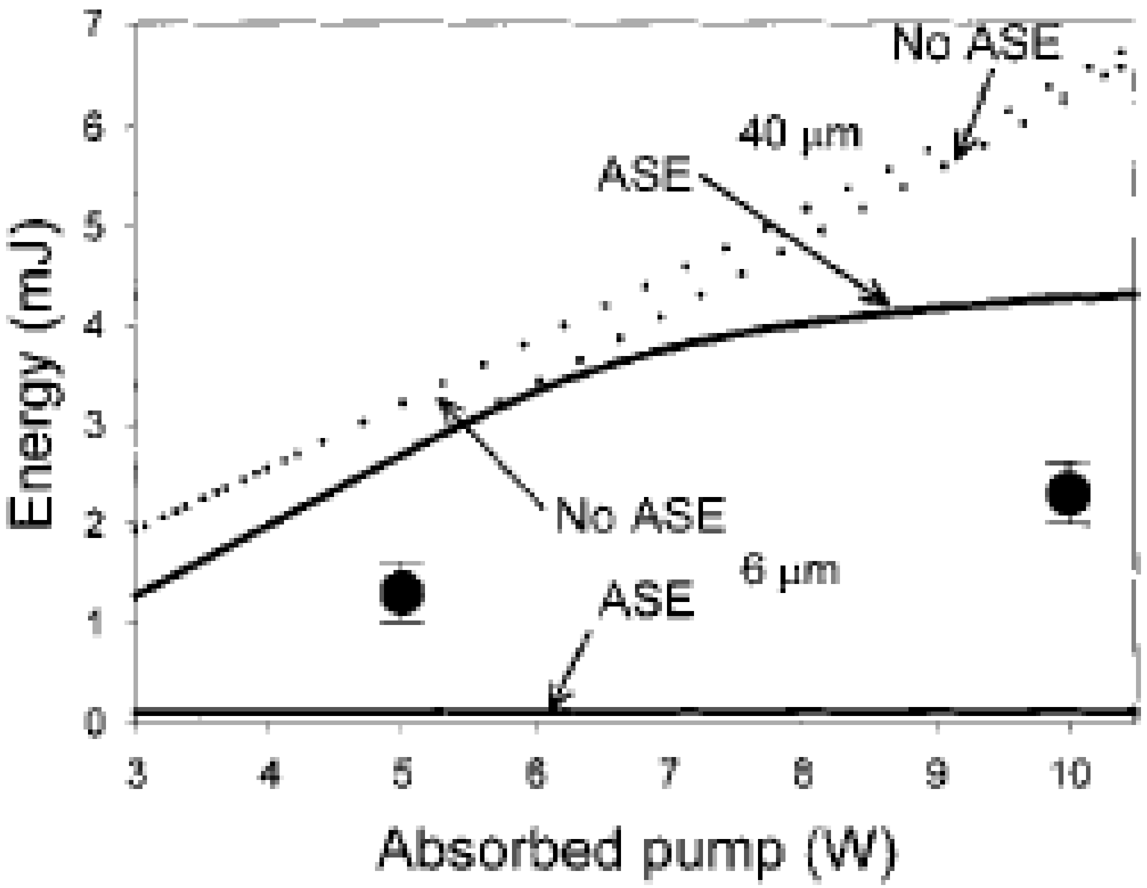
Er fiber lasers not ready for 100-mJ-level eyesafe lidar/ladar sources



100-Hz pulse rate 1535-nm OPO



Extractable energy from Yb-doped fibers limited by ASE at low pulse rates



Renaud *et al.* JQE 37, 199 (2001)

LLNL surface damage data for fused silica

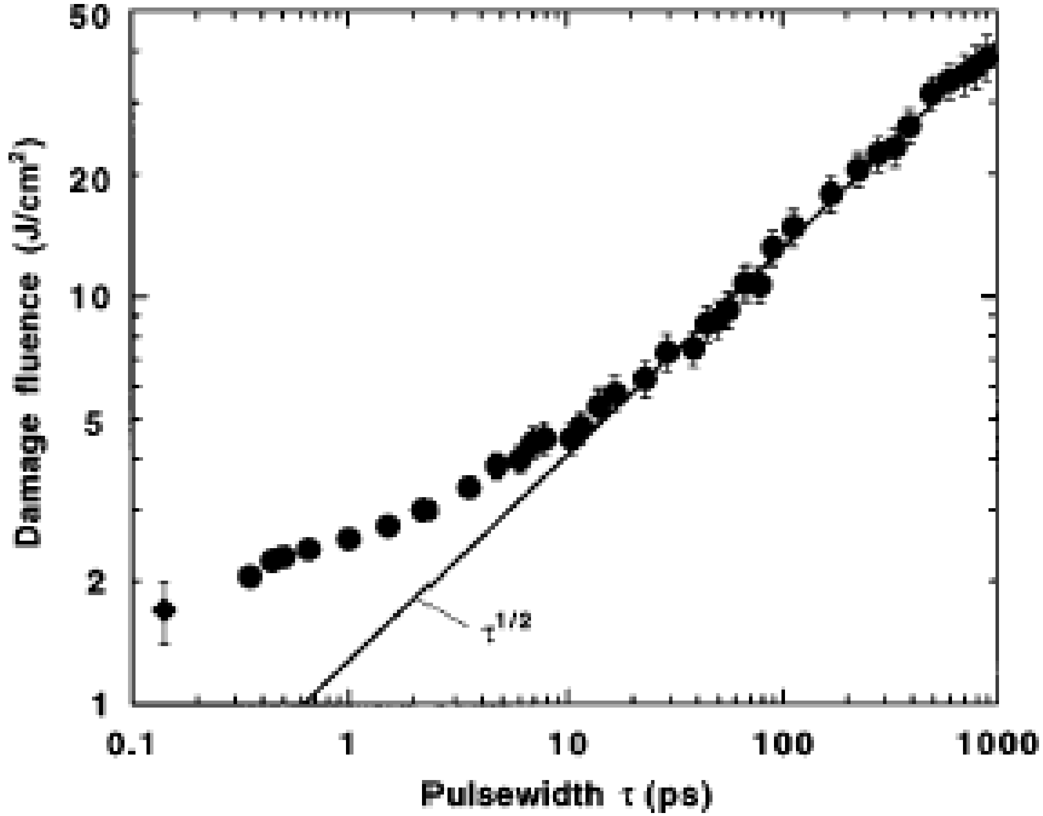
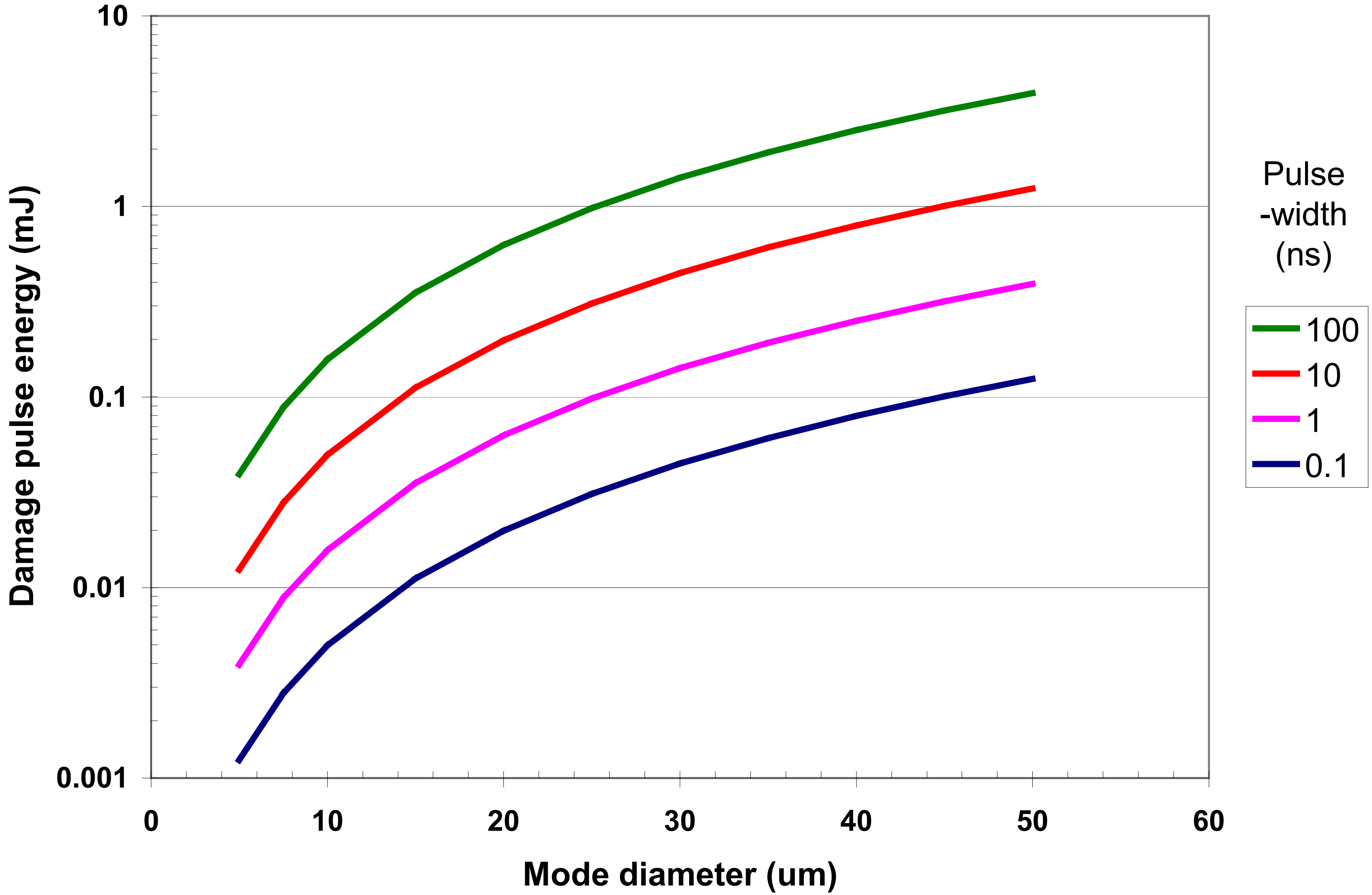


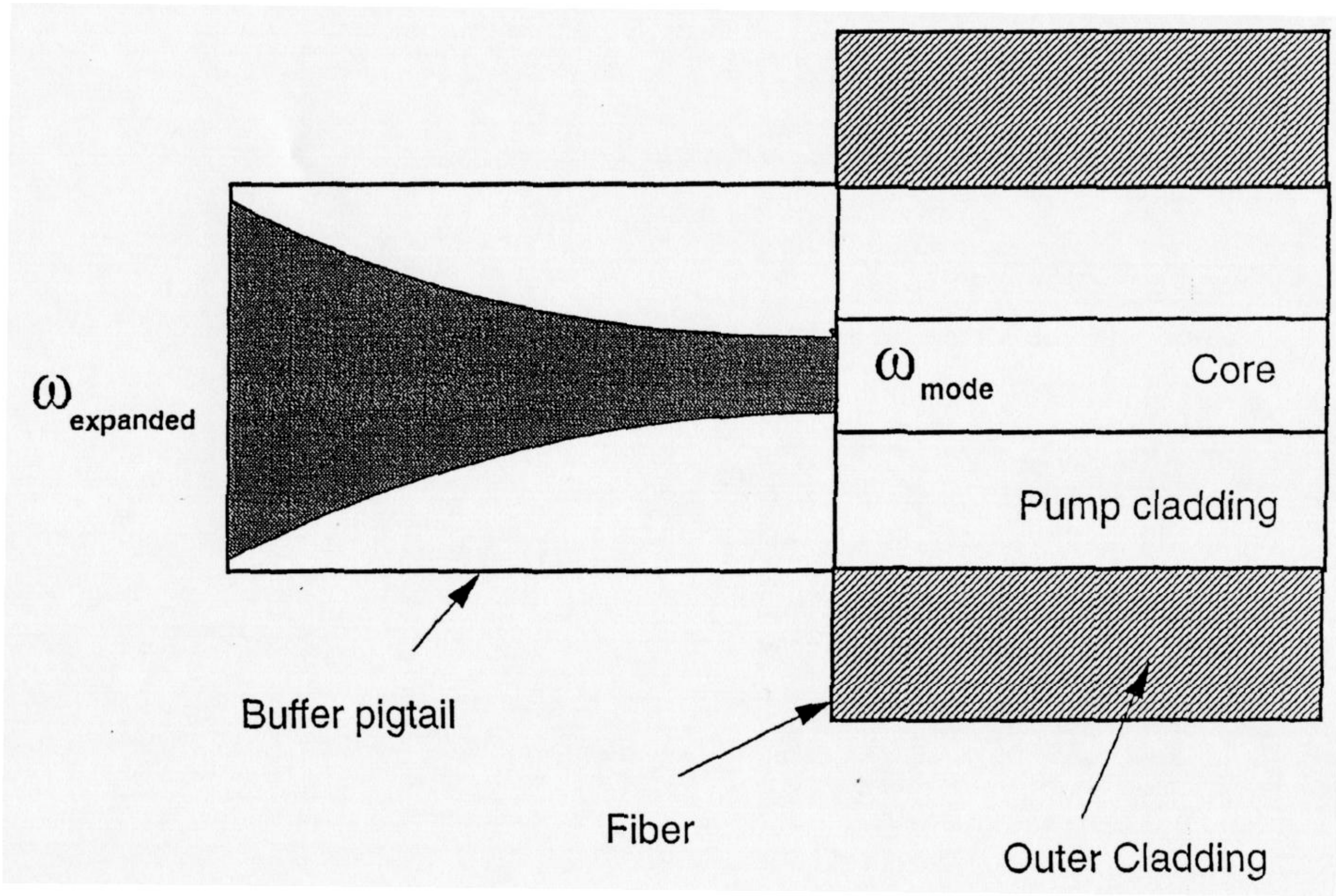
Fig. 5. Pulsewidth dependence of threshold damage fluence for fused silica at 1053 nm (●) and 825 nm (◆).

B. C. Stuart, M. D. Feit, S. Herman, A. M. Rubenchik, B. W. Shore, and M. D. Perry
J. Opt. Soc. Am. B, 459 (1996).

End-face damage limits (calculated) for different pulsewidths



Elegant solution to fiber end-face damage



IMRA Pat. App. US2004/00369587 A1

Latest pulsed fiber-laser results

- **CLEO 2004 Paper CTuS4 M-Y Chen *et al.* (U. Mich, OADS)**
- **With Yb-doped, 200 um NA 0.062, core, 600 um clad, coiled fiber**
  - **82 mJ in 500 ns**
  - **27 mJ in 50 ns**
  - **9.6 mJ in 4 ns (2.4 MW)**
- **M^2 = 6.5, 25 Hz, pump energy 560-800 mJ in 4 ms**
- **Used end-caps, but now close to bulk-damage, self-focusing limits in silica**

100-W average power, Yb pulsed fiber laser

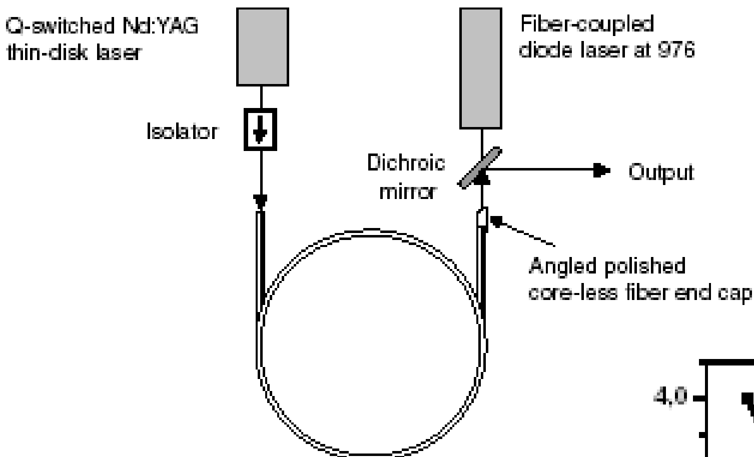


FIGURE 1 Experimental setup

25 m 30 um core NA 0.06 V=5
500 ppm Yb_2O_3
Coiled < 10 cm radius
End cap, exit beam 150 um radius
200 W pump laser
100 GHz linewidth Nd:YAG seed

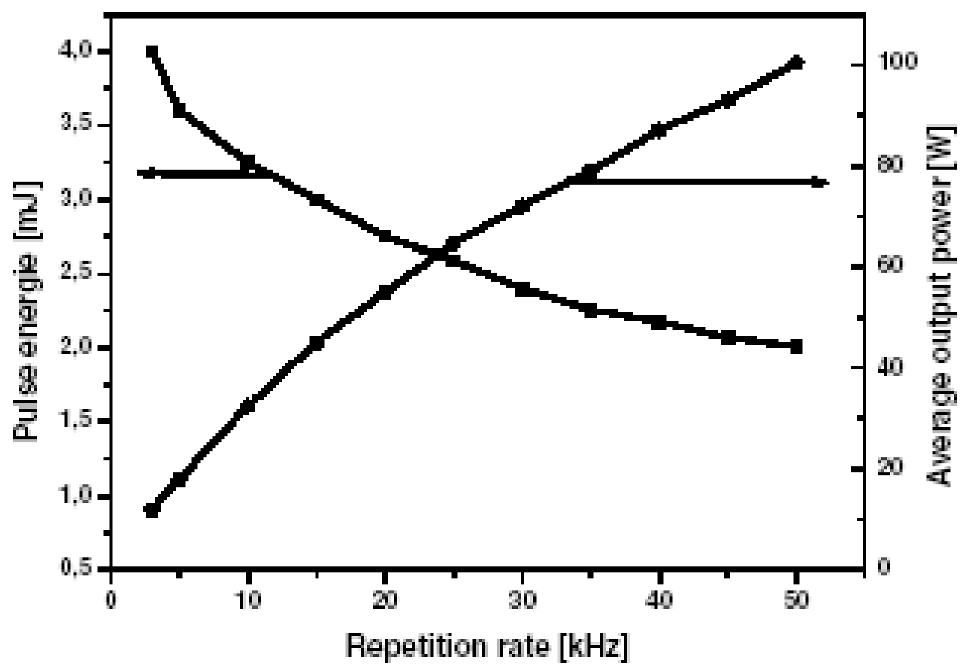
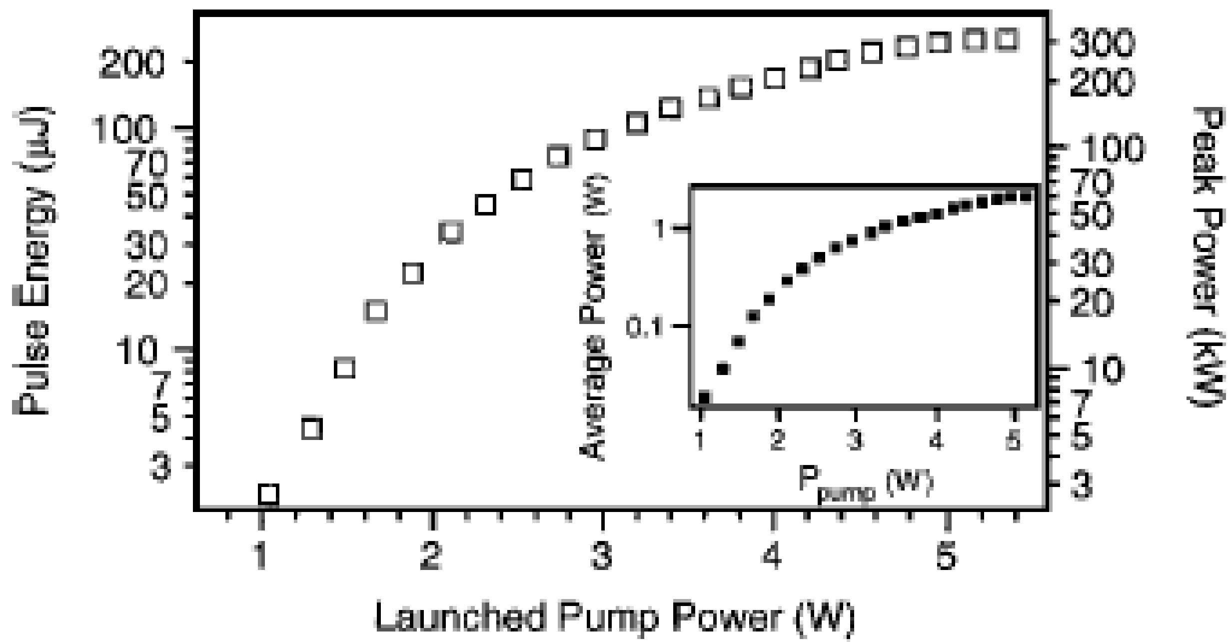


FIGURE 2 Extracted pulse energy and average power as a function of pulse repetition rate

50 ns pw at 3 kHz (80 kW)
300 ns pw at 50 kHz (6.7 kW)
100 W average at 50 kHz
M^2 = 1.1, unpolarized

J. Limpert *et al.*
Appl. Phys. B 75, 477 (2002)

305 kW peak power with 0.8 ns, transform-limited seed pulse

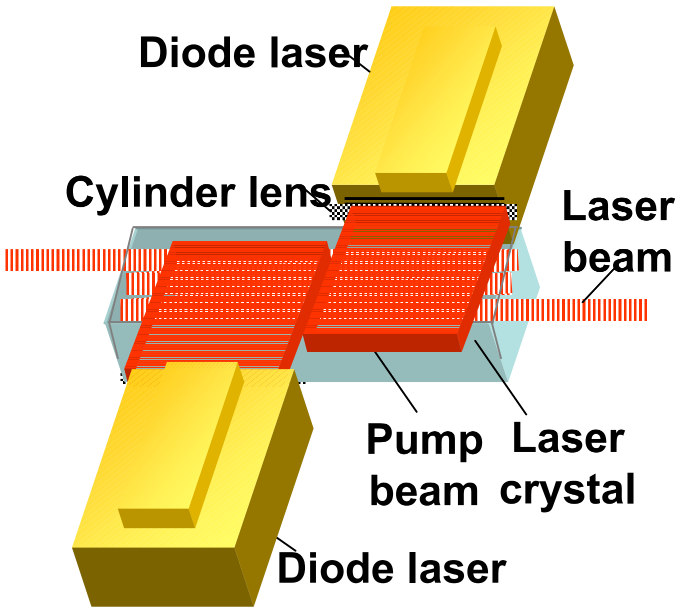


Seed laser: 1064-nm, Nd:YAG uchip at 8.5 kHz PRR
Fiber: 25 um core, 0.10 NA, V = 7.4, 7 m long, 1.67 cm dia. coil, end cap

Output: 255 uJ, 0.825 ns PW, 305 kW peak, 2.2 W ave.
Unpolarized, SRS-limited energy (Brillouin circumvented by short pulse)

F. Di Teodoro, J. P. Koplow, S.W. Moore and D. A. V. Kliner, Opt. Lett. 27, 518 (2002)

MPS design for high-efficiency, TEMoo-mode systems

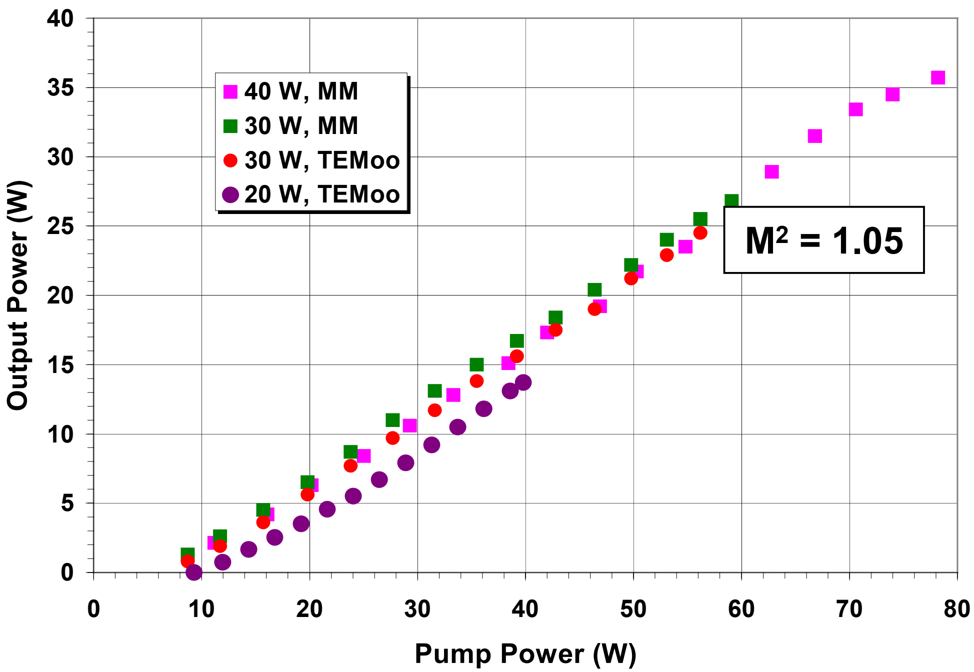


Multi-Pass Slab (MPS)

Nd:YLF is “athermal” material
0.5 diopter lens at 80 W pump

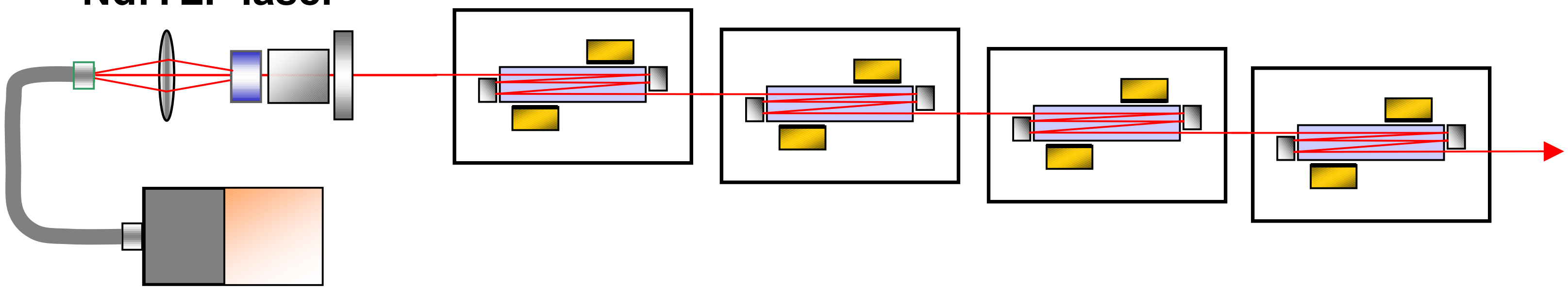
Birefringence eliminates depolarization

I/O performance with Nd:YLF at 1047 nm cw oscillator



MPS Nd:YLF amplifier chain extracts 20-25 W per stage with minimal beam degradation

Short-pulse,
AO Q-switched
Nd:YLF laser



30-100 kHz, 6.5-20 nsec
1.5 W average

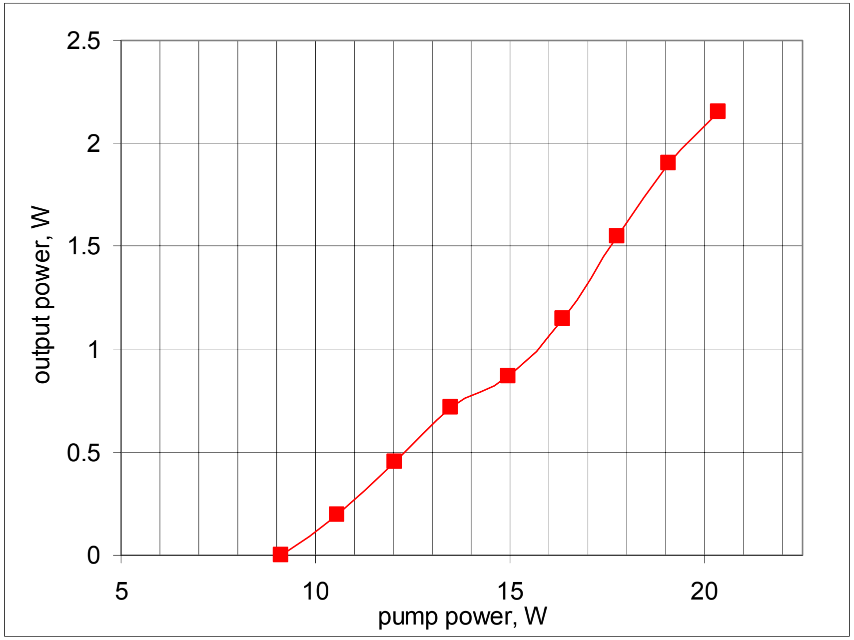
85 W average power at 1047 nm
for 250 W of diode power
At 30 kHz:
2.8 mJ/pulse
6.5 ns
435 kW
polarized
$M^2 < 1.3$

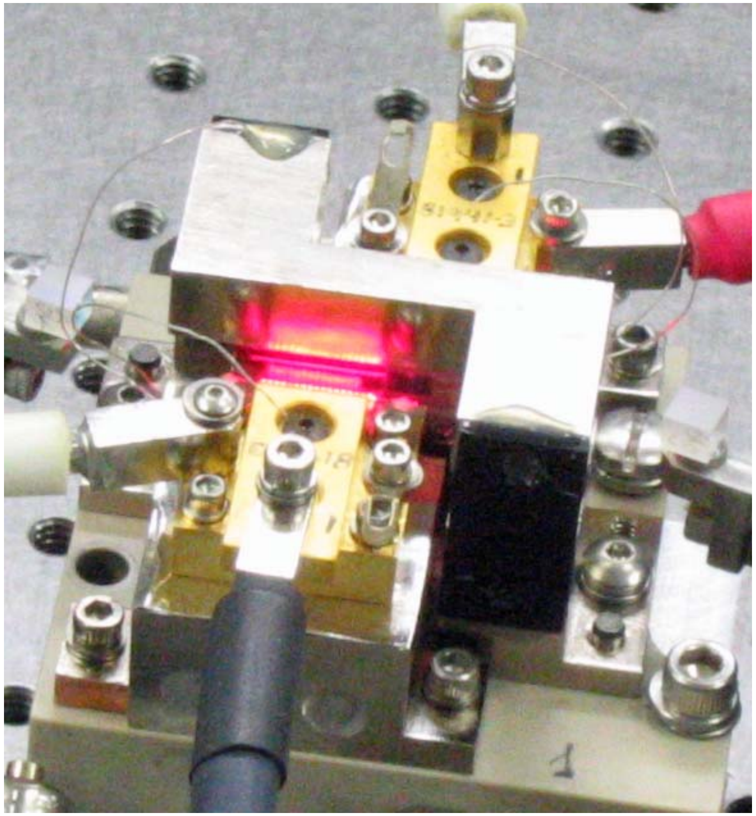
Highlights of ultrafast fiber laser systems

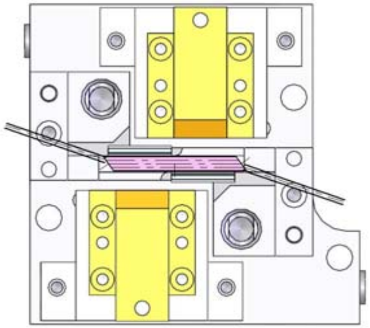
- IMRA [JQE Sel. Top. 7, 504 (2001)]
  - Fiber-based seed laser stretched to 800 ps, 10-nm BW
  - Amplified to 1.2 mJ at 1.7 kHz pulse rate, 1055 nm
  - Yb fiber, 50 um core (V=15), 2.6 m long
  - Compressed to 380 fs, 0.6 mJ

- Tunnerman group, Jena [TOPS Vol. 83, 414 (2003)]
  - Seed Nd:glass 75 MHz, 144 fs, stretched to 224 ps, 20 nm BW
  - Amplified to 140 W average power, M^2 = 1.1
  - Yb fiber, 28.5 um core, 0.06 NA, pumped by 250 W
  - Compressed to 400 fs, 76 W

Diode-pumped Cr:LiSAF laser generates > 2 W cw power at 850 nm







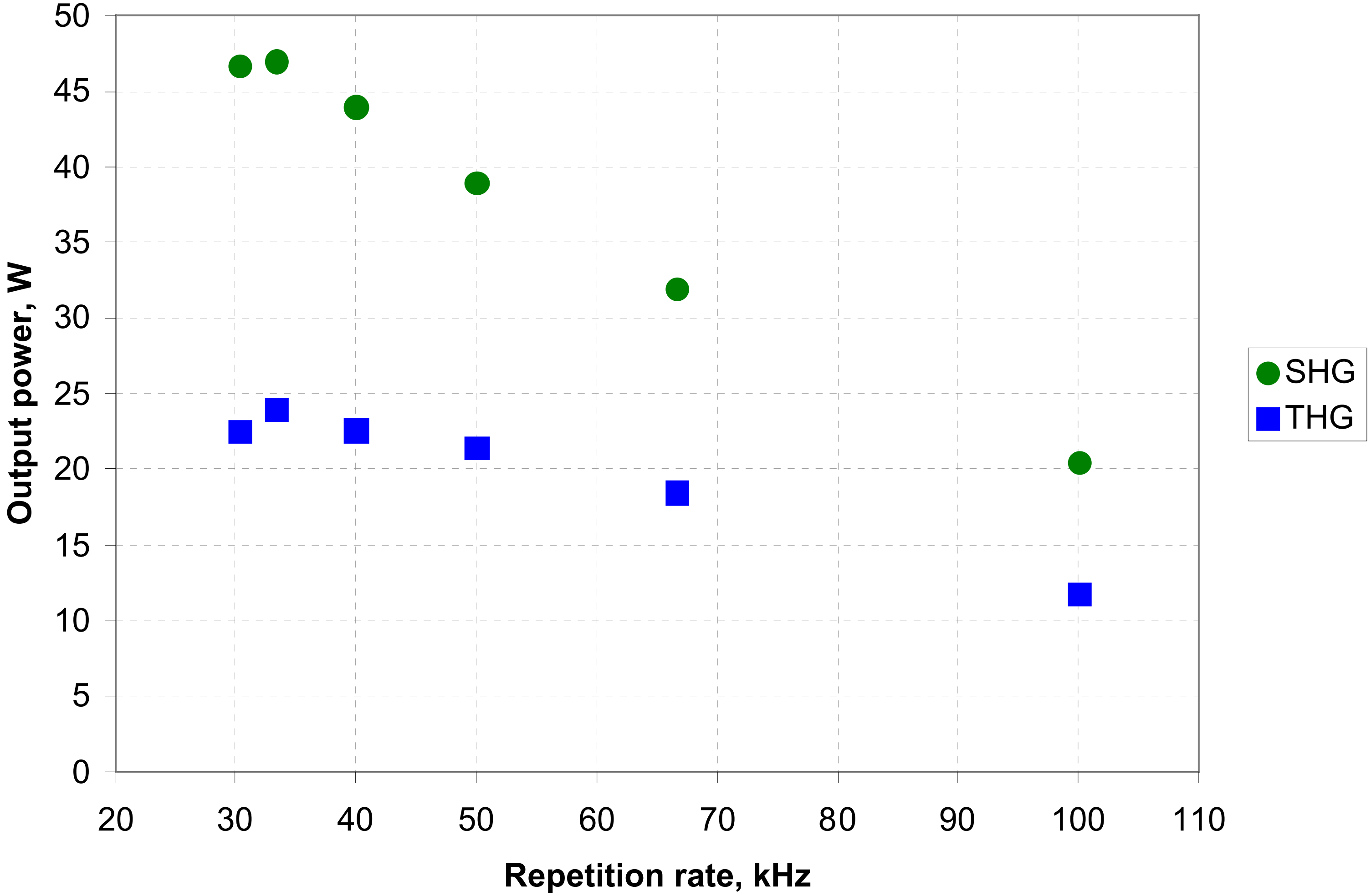
Cr:LiSAF has the bandwidth to support 10 fs pulses

Driving nonlinear optics

Fiber lasers and harmonic generation

- Periodically poled materials are a good match to the relatively low peak powers from pulsed fiber lasers
- Taylor/IPG (ASSP 2004, paper TuA5)
  - DFB seed source 12 MHz, 2.5 ns
  - Yb-Er fiber preamps and final 12 um core , 7 m amplifier
  - 33 W average, 1.2 kW peak power
  - PPKTP doubler, 25 W out, 75.6% conversion
  - *3.5 W UV (387 nm) in LBO, CLEO 2004 CMM2, CTuI5*
- But, robustness of PP materials in green and shorter wavelengths an issue. Also, limited spectral bandwidth requires narrow source.
- Higher peak powers from ultrafast sources permits use of borates
  - Tunnerman group reported 24 W green in LBO driven by 48 W, 10 ps pulses at 80 MHz, with PCF fiber amplifier

Bulk lasers provide the peak and average powers needed for high-power UV generation

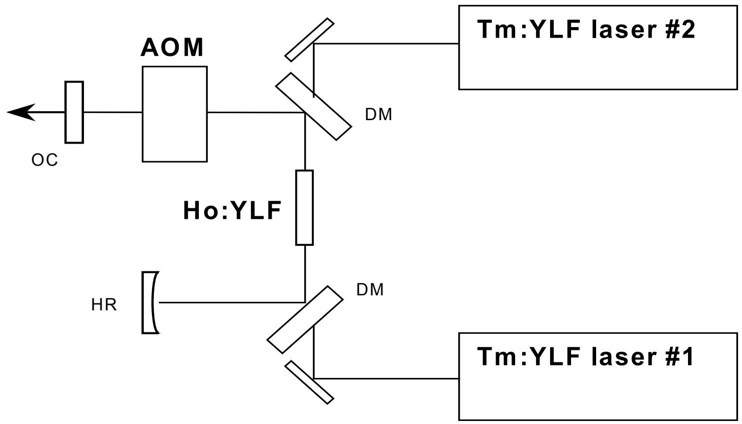


Fiber and bulk lasers working together

Q-peak

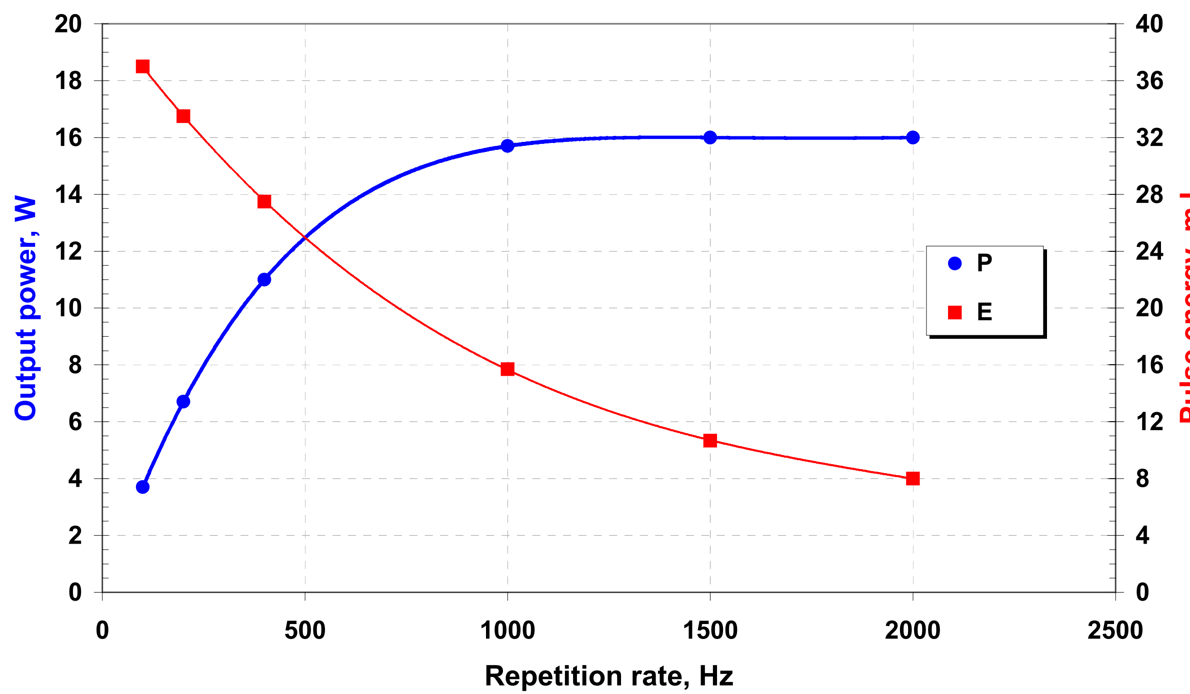
APPLIED PHOTONIC SYSTEMS

Scale-up of Ho:YLF-driven ZGP OPO will use 350 W of Tm-fiber-laser pumping



Present pump source employs two, 25 W Tm:YLF lasers

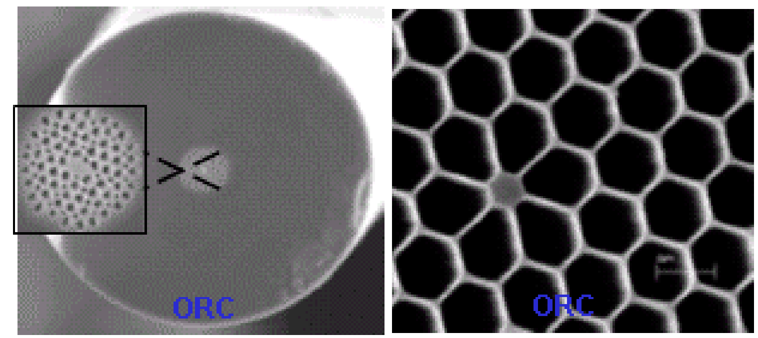
Ho:YLF has 15 ms storage lifetime, generates 37 mJ at 2050 nm in 12 nsec pulse



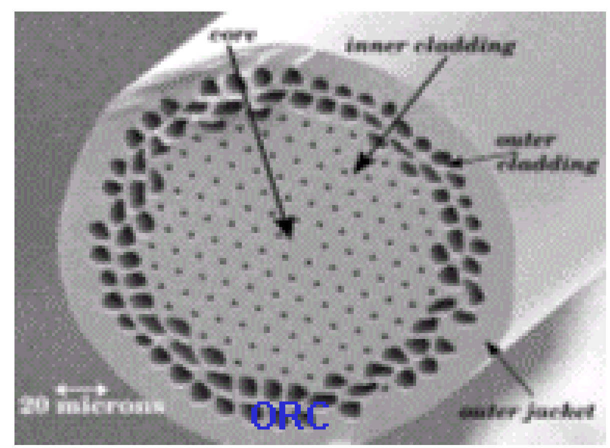
Future directions - photonic fibers

PCF fundamentals

- Photonic crystal (or holey) fibers are fabricated with structured “holes” in fiber cross section
- The region with holes has a lower and adjustable refractive index, with tunable dispersive properties
- For fiber lasers, applications include:
  - Replacing polymer cladding with low-index holey section, eliminating chance of polymer “burn” and increasing NA of cladding
  - Allowing very low refractive change, for larger core mode sizes (reduced bending losses observed)

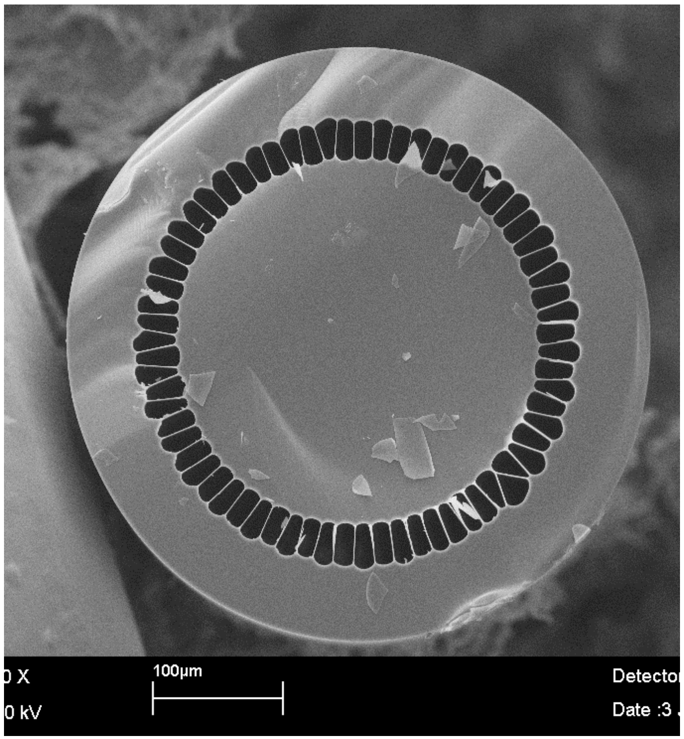


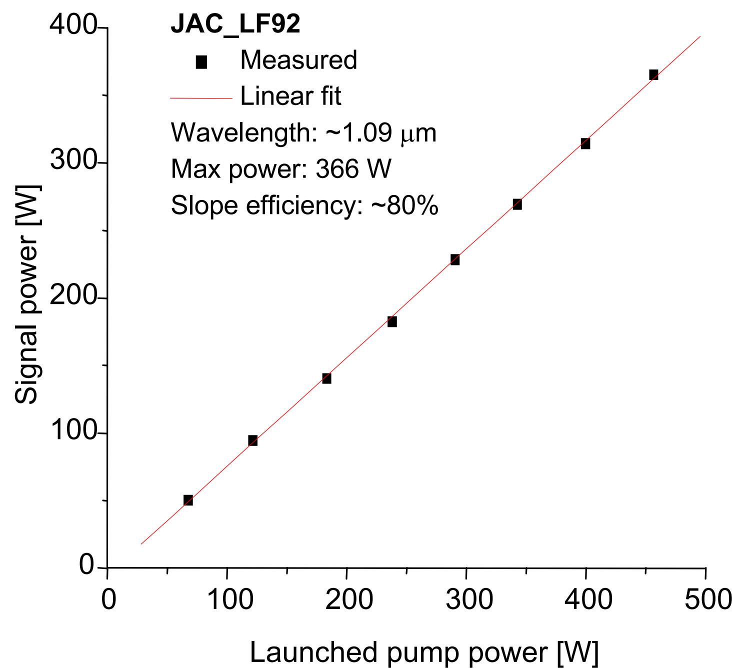
Small-core high effective nonlinearity HFs



Cladding-pumped Yb^{3+} doped HF

ORC 366 W Yb fiber laser with “air jecket”





Y. Jeong, Southampton, LEOS 2003 Annual

Also: J. Limpert *et al.* Thermo-optical properties of air-clad photonic crystal fiber lasers in high power operation, Opt. Ex. 11, 2982 (2003)

Conclusions

- **Fiber lasers have reached cw power levels formerly only possible with bulk-crystal designs, and have somewhat better beam quality**
- **The simplifications in cooling the active medium compared to bulk lasers are countered by the need for higher-brightness pump sources**
  - **"Side-pumped" schemes (IPG, SPI) are advantageous**
- **Acceptance of competing technologies (rod, thin disk and fiber) for materials processing will depend on factors other than beam quality, total cost of ownership being the most significant**
- **For short-pulsed systems, bulk lasers will "always" be capable of higher energies and peak powers, but fiber lasers can provide a new operation space (e.g. MHz pulse rates) that would be difficult with bulk systems**