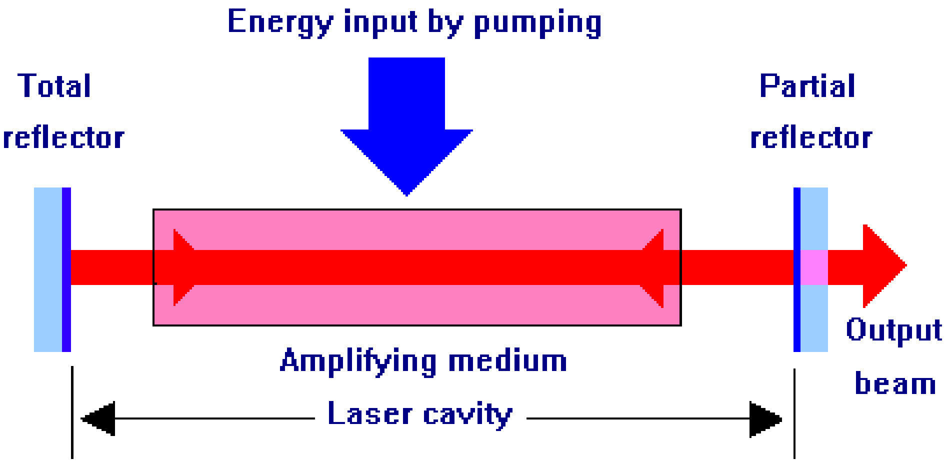
Recent Progress in Active Fiber Designs and Monolithic High Power Fiber Laser Devices

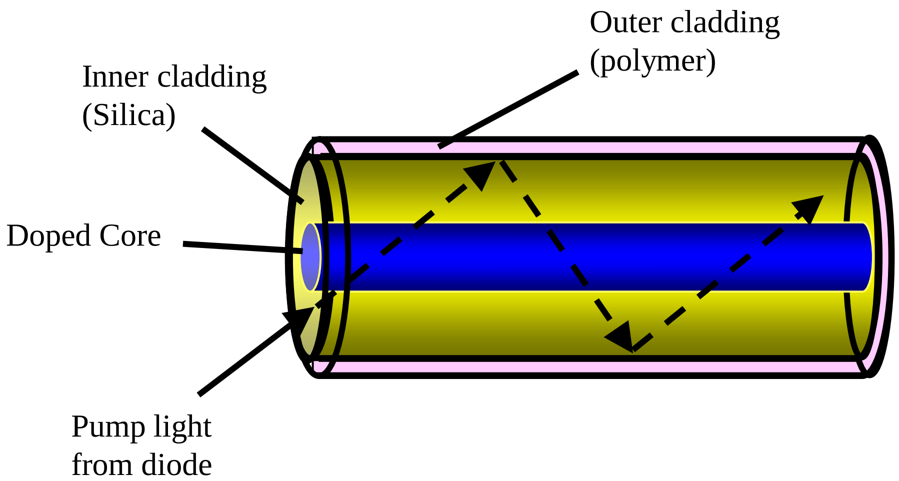
Kanishka Tankala, Adrian Carter and Bryce Samson

Advantages of Fiber Lasers

Features	Benefits
Highly efficient diode pumped operation (20-30 % wall plug efficiency)	Lower cost of ownership (service requirements)
Easy thermal management	Lower cooling requirements (air-cooled operation)
Robust, reliable all-fiber monolithic design	Low mantainance No cavity optics to adjust or align
Excellent beam quality M^2 ~1, TEM_{00}	Small focal spot size Long depth of focus
High power 1 micron output	Fiber deliverable output direct to workpiece
Compact and lightweight	Uses less floor space and is mountable/flyable

Fiber Laser Advantage - Efficiency





Laser	Optical-optical efficiency	Wall plug efficiency
Lamp-pumped YAG	4%	1%
Diode-pumped YAG	40-50 %	6%
Yb:YAG Disk	40-50 %	20%
CO2	N/A	10%
Yb:Glass fiber	>75%	20-30 %

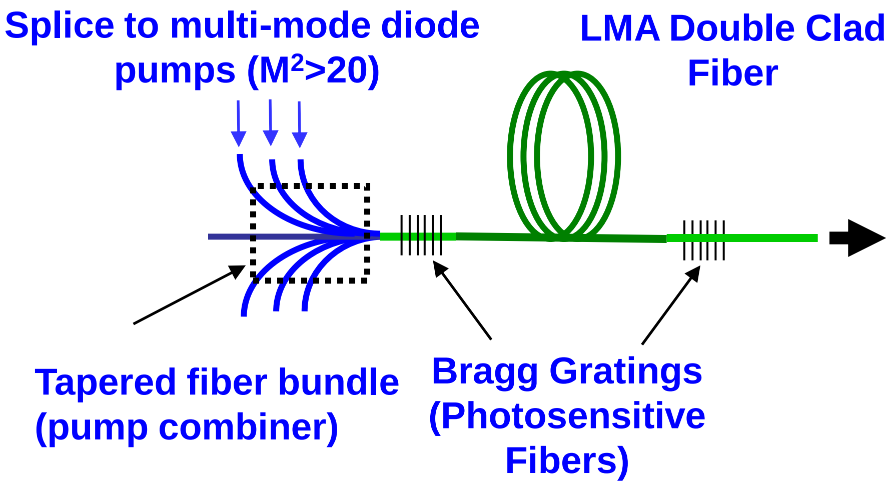
The inherent efficiency of the fiber laser is unrivalled when compared to existing conventional laser technologies.

Advantages of Fiber Lasers - Beam Quality
(Beam Parameter Product and Depth of Focus)

	CO_2 Lasers	Lamp-pumped Nd:YAG	Diode-pumped Nd:YAG	Yb:YAG Disk	Yb:Glass Fiber
BPP	6 mm.mrad	25 mm.mrad	12 mm.mrad	6 mm.mrad	**0.34 mm.mrad**
DOF (mm) at given focused spot size					
400 microns	13.3 mm	3.2 mm	6.6 mm	13.3 mm	**235 mm**
200 microns	3.3 mm	0.8 mm	1.6 mm	3.3 mm	**58.8 mm**

- Fiber lasers have 10-30X greater depth of focus (DOF) than CO_2 lasers
  - intense focal region is maintained over an extended distance
- Process Advantages
  - thicker materials with smaller kerf
  - larger distance from work piece
  - Smaller, focused beams: high resolution at higher speeds
- Design and Maintenance Costs
  - Smaller spot size can be obtained with less beam expansion
    - smaller, less expensive lenses
    - faster, smaller and less expensive galvo-mirrors
  - Lower maintenance to protect optics from heat, reflections, debris, etc

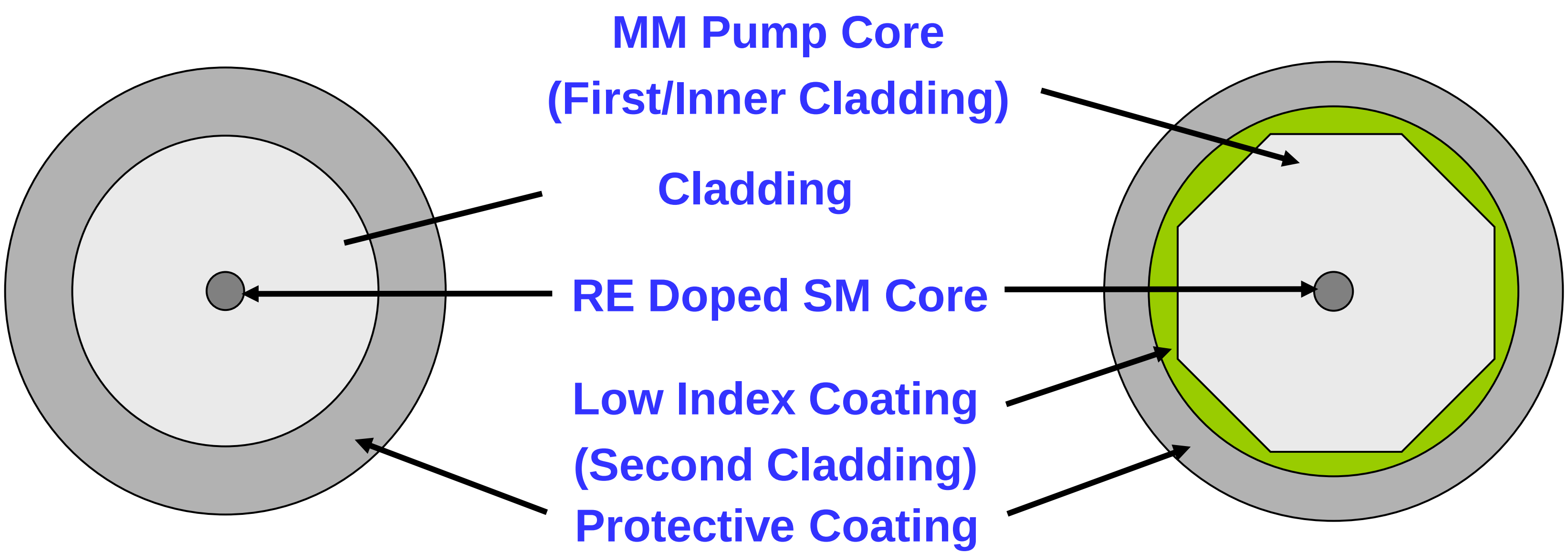
Fiber Laser Advantage – Robust and Reliable



- Fiber lasers architecture is monolithic (entire laser is in the fiber)
  - Doped fiber core is the gain media
  - Fiber cladding is the “pump chamber”
  - The output coupler and high reflector are Bragg Gratings written into the fiber core.
  - The pump diodes may be spliced directly to the active fiber (cavity)

- Monolithic all-fiber architecture is *inherently* more reliable than free space (exposed) optics with adjustable mechanics (alignment sensitive) of conventional laser
- The beam quality will NOT change over the lifetime of the laser

Double Clad (Cladding Pumped) Fibers

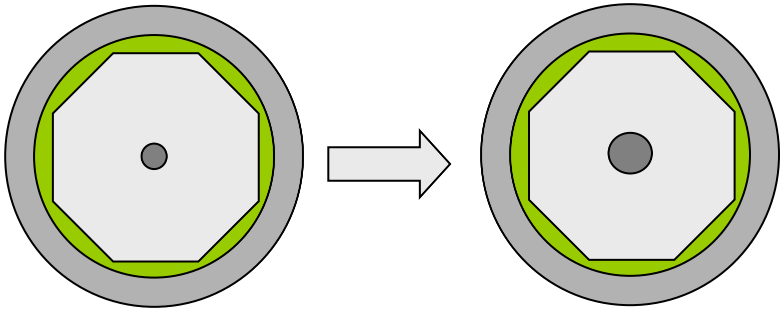


- First cladding pump design (Snitzer, 1988)
  - Removed requirement for core pumping
- Brightness converter:
  - Input: low-cost, large-area, high-power semi-conductor source
  - Output: high brightness output
- High power output (SM core) limited by SRS (~125 W, IPG)

Power Scaling in Single Mode Fibers

- **Fiber Design**:
  - Increase core ϕ by reducing NA
    ⇨ decrease power density
    ⇨ increase NL thresholds
  - If V-value is < 2.405 fiber is SM

$$V = \frac{\pi d_{core} NA_{core}}{\lambda}$$



3 -10micron (0.2-0.1NA)

10 -15micron (0.1-0.06NA)

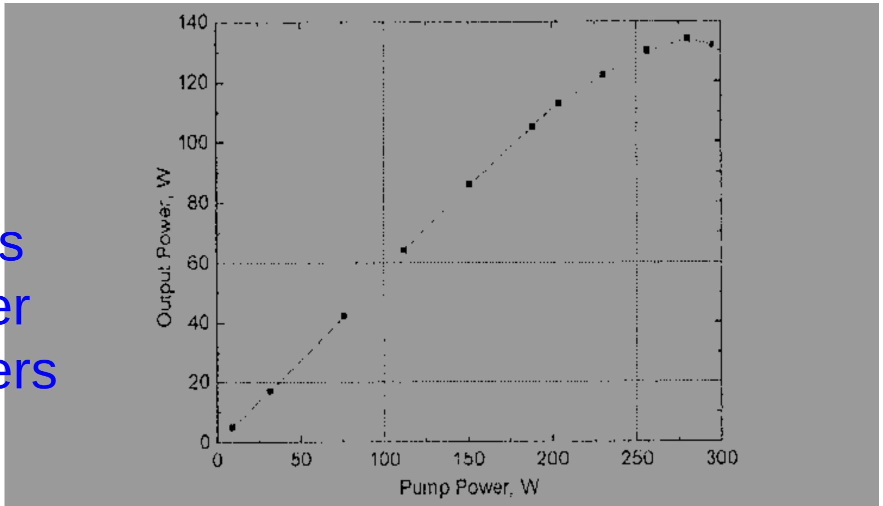
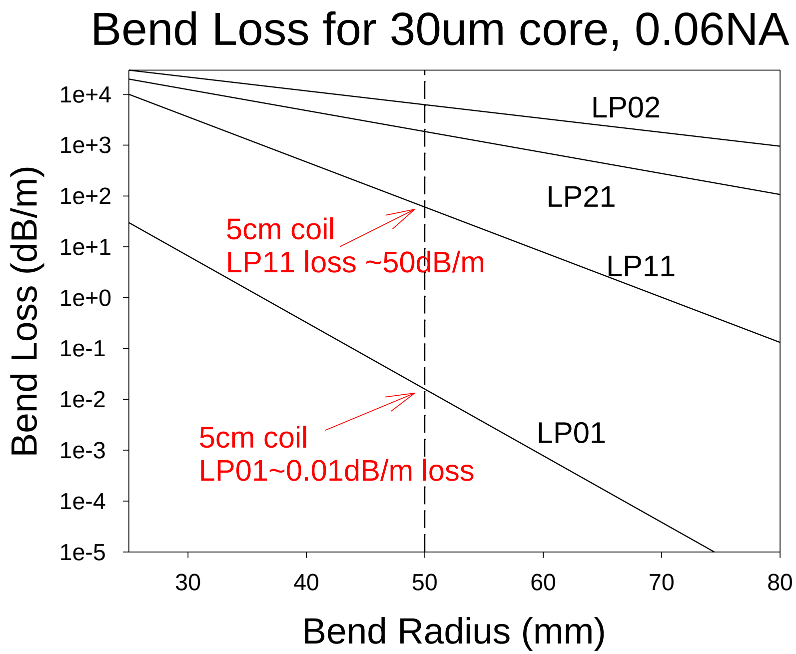


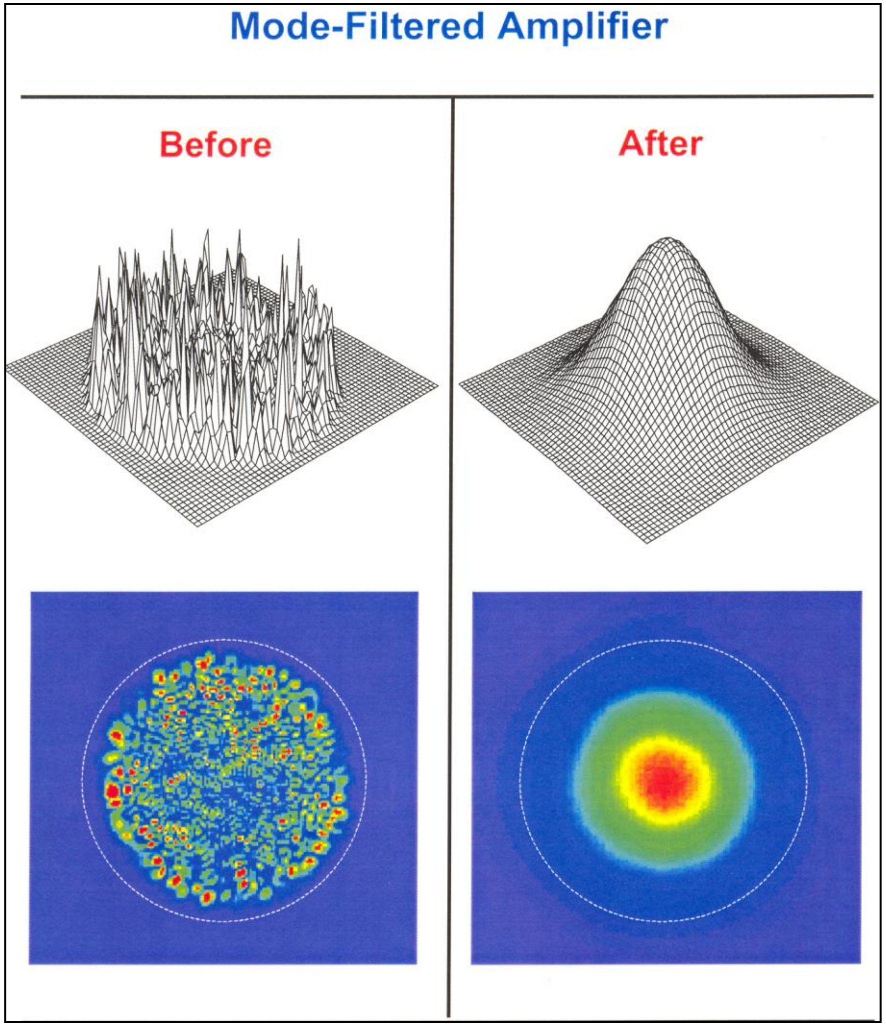
Figure 2: Output optical power versus pump power

- **Limitations**:
  - Optical nonlinearities (NL) such as SRS, SBS, SPM, FWM limit power scaling in small core, high NA fibers
  - Small cores limit energy storage capacity for pulsed applications

Large Mode Area Fibers



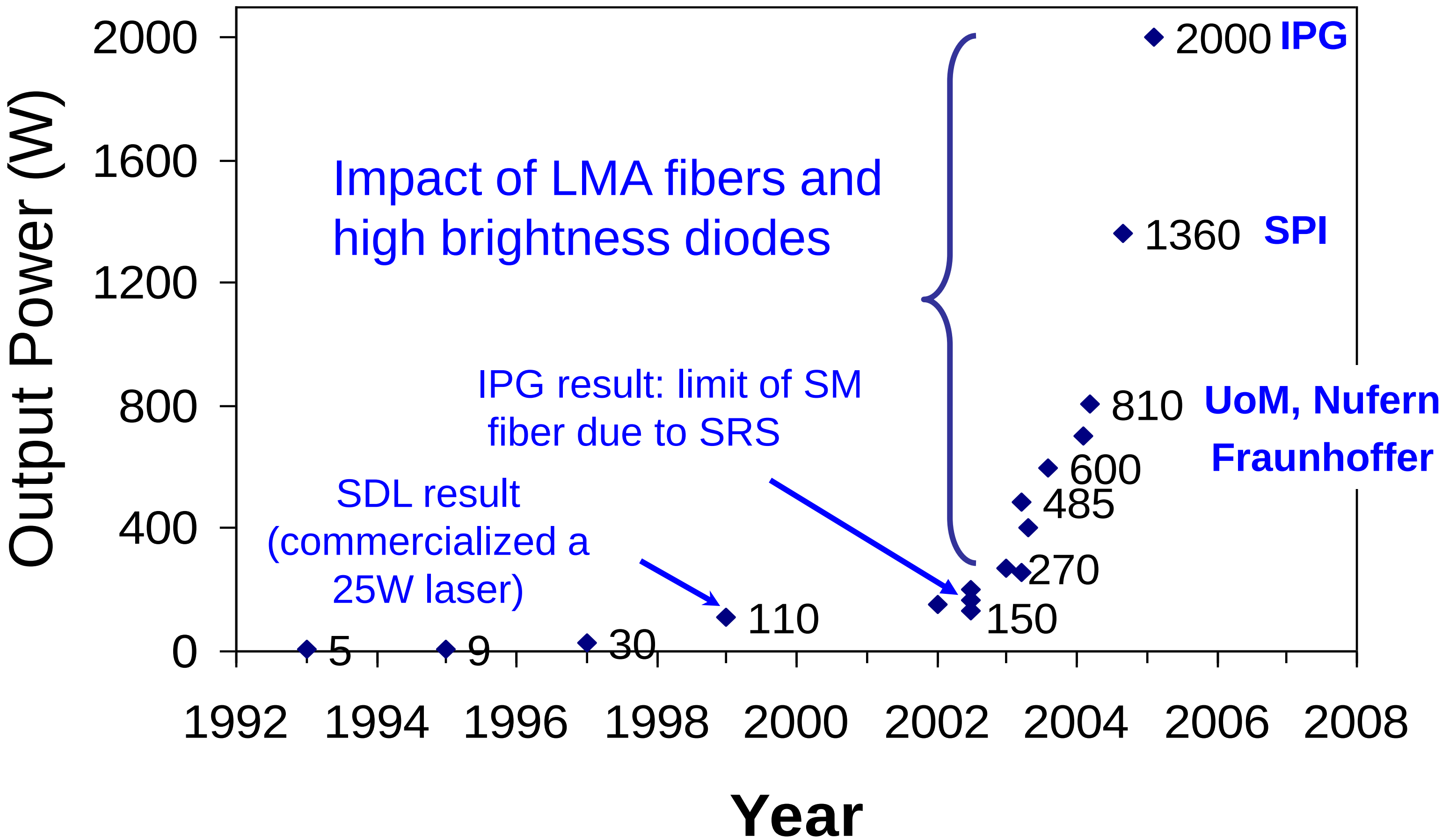
- LMA fibers use low NA, MM cores to limit nonlinearities
- Techniques such as coiling are used to achieve a diffraction limited beam



Courtesy D. Kliner, Sandia National Labs

Power Scaling with LMA Fibers

Broadband diffraction limited output from single strand of fiber



Fiber lasers are a viable alternative to more conventional solid state lasers

Yb-doped LMA "Standard" fibers

20µm core, 0.06NA
V~3.7 at 1080nm
Core supports two modes
Easy to deliver good beam quality
Large cladding enables various pump options

10/400 Ytterbium-Doped
Double Clad Fiber

OPTICAL SPECIFICATIONS	PLMA-YDF-10/400	LMA-YDF-10/400
Operating Wavelength (nominal)	1060 - 1115 nm	1060 - 1115 nm
Cladding Absorption @ 915 nm	0.25 ± 0.10 dB/m	0.25 ± 0.10 dB/m
Peak Cladding Absorption @ 975 nm (nominal)	0.8 dB/m	0.8 dB/m
Second Mode Cut-Off	970 ± 70 nm	970 ± 70 nm
Core Numerical Aperture	0.075	0.075
Cladding Numerical Aperture (nominal)	0.46	0.46
Cladding Attenuation @ 1100 nm (nominal)	< 0.01 dB/m	< 0.01 dB/m
Birefringence	$\geq 3.5\times10^{-4}$	NA
GEOMETRICAL AND MECHANICAL SPECS		
MFD @ 1080 nm ($1/e^2$ fit)	11.5 ± 2 µm	11.5 ± 2 µm
Clad Diameter	400 ± 15 µm	400 ± 15 µm
Coating Diameter	550 ± 20 µm	550 ± 20 µm
Outer Cladding Material	Low Index Polymer	Low Index Polymer

Applications:
- High power fiber lasers
- CW amplifiers
- Military, industrial and medical
- Single-mode applications

Features and Benefits:
- Low NA core
- Mode field area several times larger than standard double clad fibers
- Large, high NA cladding
- Compatible with high power diode pumping

Standard specifications and design parameters are listed above. Other configurations may be available. Let us know how Nufern can assist with your requirements. Call 860-408-5000, toll free at 866-466-0214 or email us at info@nufern.com.

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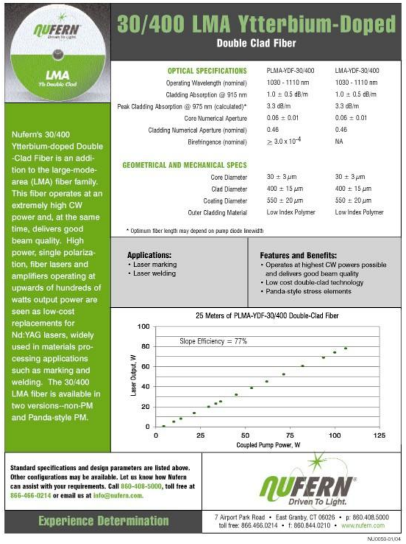

30/400 LMA Ytterbium-Doped
Double Clad Fiber

Nufern's 30/400 Ytterbium-doped Double-Clad Fiber is an addition to the large-mode-area (LMA) fiber family. This fiber operates at an extremely high CW power and, at the same time, delivers good beam quality. High power, single polarization, fiber lasers and amplifiers operating at upwards of hundreds of watts output power are seen as low-cost replacements for Nd:YAG lasers, widely used in materials processing applications such as marking and welding. The 30/400 LMA fiber is available in two versions--non-PM and Panda-style PM.

OPTICAL SPECIFICATIONS	PLMA-YDF-30/400	LMA-YDF-30/400
Operating Wavelength (nominal)	1030 - 1110 nm	1030 - 1110 nm
Cladding Absorption @ 915 nm	1.0 ± 0.5 dB/m	1.0 ± 0.5 dB/m
Peak Cladding Absorption @ 975 nm (calculated)*	3.3 dB/m	3.3 dB/m
Core Numerical Aperture	0.06 ± 0.01	0.06 ± 0.01
Cladding Numerical Aperture (nominal)	0.46	0.46
Birefringence (nominal)	$\geq 3.0 \times 10^{-4}$	NA
GEOMETRICAL AND MECHANICAL SPECS		
Core Diameter	30 ± 3 µm	30 ± 3 µm
Clad Diameter	400 ± 15 µm	400 ± 15 µm
Coating Diameter	550 ± 20 µm	550 ± 20 µm
Outer Cladding Material	Low Index Polymer	Low Index Polymer

* Optimum fiber length may depend on pump diode linewidth

Applications:
- Laser marking
- Laser welding

Features and Benefits:
- Operates at highest CW powers possible and delivers good beam quality
- Low cost double-clad technology
- Panda-style stress elements

Standard specifications and design parameters are listed above. Other configurations may be available. Let us know how Nufern can assist with your requirements. Call 860-408-5000, toll free at 866-466-0214 or email us at info@nufern.com.

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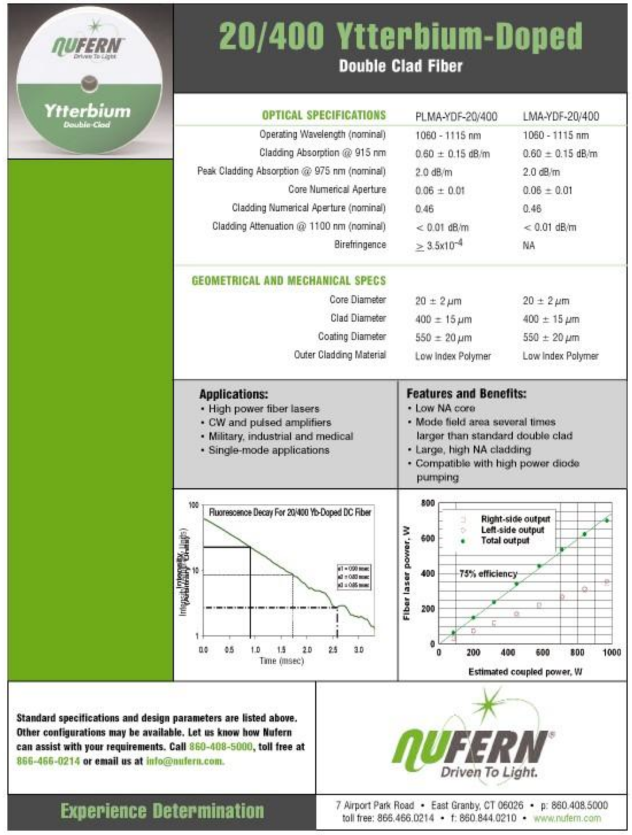

20/400 Ytterbium-Doped
Double Clad Fiber

OPTICAL SPECIFICATIONS	PLMA-YDF-20/400	LMA-YDF-20/400
Operating Wavelength (nominal)	1060 - 1115 nm	1060 - 1115 nm
Cladding Absorption @ 915 nm	0.60 ± 0.15 dB/m	0.60 ± 0.15 dB/m
Peak Cladding Absorption @ 975 nm (nominal)	2.0 dB/m	2.0 dB/m
Core Numerical Aperture	0.06 ± 0.01	0.06 ± 0.01
Cladding Numerical Aperture (nominal)	0.46	0.46
Cladding Attenuation @ 1100 nm (nominal)	< 0.01 dB/m	< 0.01 dB/m
Birefringence	$\geq 3.5\times10^{-4}$	NA
GEOMETRICAL AND MECHANICAL SPECS		
Core Diameter	20 ± 2 µm	20 ± 2 µm
Clad Diameter	400 ± 15 µm	400 ± 15 µm
Coating Diameter	550 ± 20 µm	550 ± 20 µm
Outer Cladding Material	Low Index Polymer	Low Index Polymer

Applications:
- High power fiber lasers
- CW and pulsed amplifiers
- Military, industrial and medical
- Single-mode applications

Features and Benefits:
- Low NA core
- Mode field area several times larger than standard double clad fibers
- Large, high NA cladding
- Compatible with high power diode pumping

Standard specifications and design parameters are listed above. Other configurations may be available. Let us know how Nufern can assist with your requirements. Call 860-408-5000, toll free at 866-466-0214 or email us at info@nufern.com.

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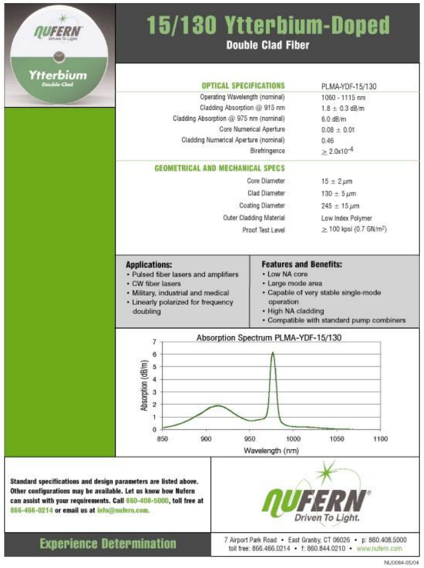

15/130 Ytterbium-Doped
Double Clad Fiber

OPTICAL SPECIFICATIONS	PLMA-YDF-15/130
Operating Wavelength (nominal)	1060 - 1115 nm
Cladding Absorption @ 915 nm	1.8 ± 0.3 dB/m
Cladding Absorption @ 975 nm (nominal)	6.0 dB/m
Core Numerical Aperture	0.08 ± 0.01
Cladding Numerical Aperture (nominal)	0.46
Birefringence	$\geq 2.0\times10^{-4}$
GEOMETRICAL AND MECHANICAL SPECS	
Core Diameter	15 ± 2 µm
Clad Diameter	130 ± 5 µm
Coating Diameter	245 ± 15 µm
Outer Cladding Material	Low Index Polymer
Proof Test Level	≥ 100 kpsi (0.7 GN/m^2)

Applications:
- Pulsed fiber lasers and amplifiers
- CW fiber lasers
- Military, industrial and medical
- Linearly polarized for frequency doubling

Features and Benefits:
- Low NA core
- Large mode area
- Capable of very stable single-mode operation
- High NA cladding
- Compatible with standard pump combiners

Standard specifications and design parameters are listed above. Other configurations may be available. Let us know how Nufern can assist with your requirements. Call 860-408-5000, toll free at 866-466-0214 or email us at info@nufern.com.

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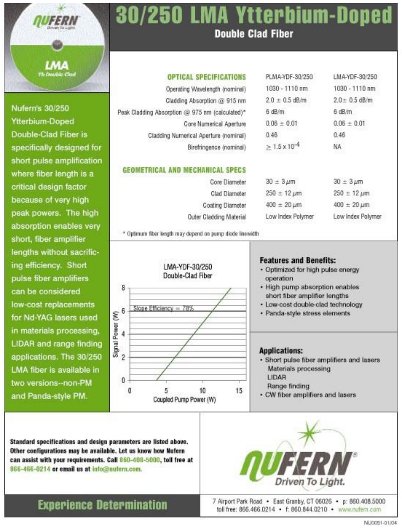

30/250 LMA Ytterbium-Doped
Double Clad Fiber

Nufern's 30/250 Ytterbium-Doped Double-Clad Fiber is specifically designed for short pulse amplification where fiber length is a critical design factor because of very high peak powers. The high absorption enables very short, fiber amplifier lengths without sacrificing efficiency. Short pulse fiber amplifiers can be considered low-cost replacements for Nd-YAG lasers used in materials processing, LIDAR and range finding applications. The 30/250 LMA fiber is available in two versions--non-PM and Panda-style PM.

OPTICAL SPECIFICATIONS	PLMA-YDF-30/250	LMA-YDF-30/250
Operating Wavelength (nominal)	1030 - 1110 nm	1030 - 1110 nm
Cladding Absorption @ 915 nm	2.0 ± 0.5 dB/m	2.0± 0.5 dB/m
Peak Cladding Absorption @ 975 nm (calculated)*	6 dB/m	6 dB/m
Core Numerical Aperture	0.06 ± 0.01	0.06 ± 0.01
Cladding Numerical Aperture (nominal)	0.46	0.46
Birefringence (nominal)	$\geq 1.5 \times 10^{-4}$	NA
GEOMETRICAL AND MECHANICAL SPECS		
Core Diameter	30 ± 3 µm	30 ± 3 µm
Clad Diameter	250 ± 12 µm	250 ± 12 µm
Coating Diameter	400 ± 20 µm	400 ± 20 µm
Outer Cladding Material	Low Index Polymer	Low Index Polymer

* Optimum fiber length may depend on pump diode linewidth

Features and Benefits:
- Optimized for high pulse energy operation
- High pump absorption enables short fiber amplifier lengths
- Low-cost double-clad technology
- Panda-style stress elements

Applications:
- Short pulse fiber amplifiers and lasers
  Materials processing
  LIDAR
  Range finding
- CW fiber amplifiers and lasers

Standard specifications and design parameters are listed above. Other configurations may be available. Let us know how Nufern can assist with your requirements. Call 860-408-5000, toll free at 866-466-0214 or email us at info@nufern.com.

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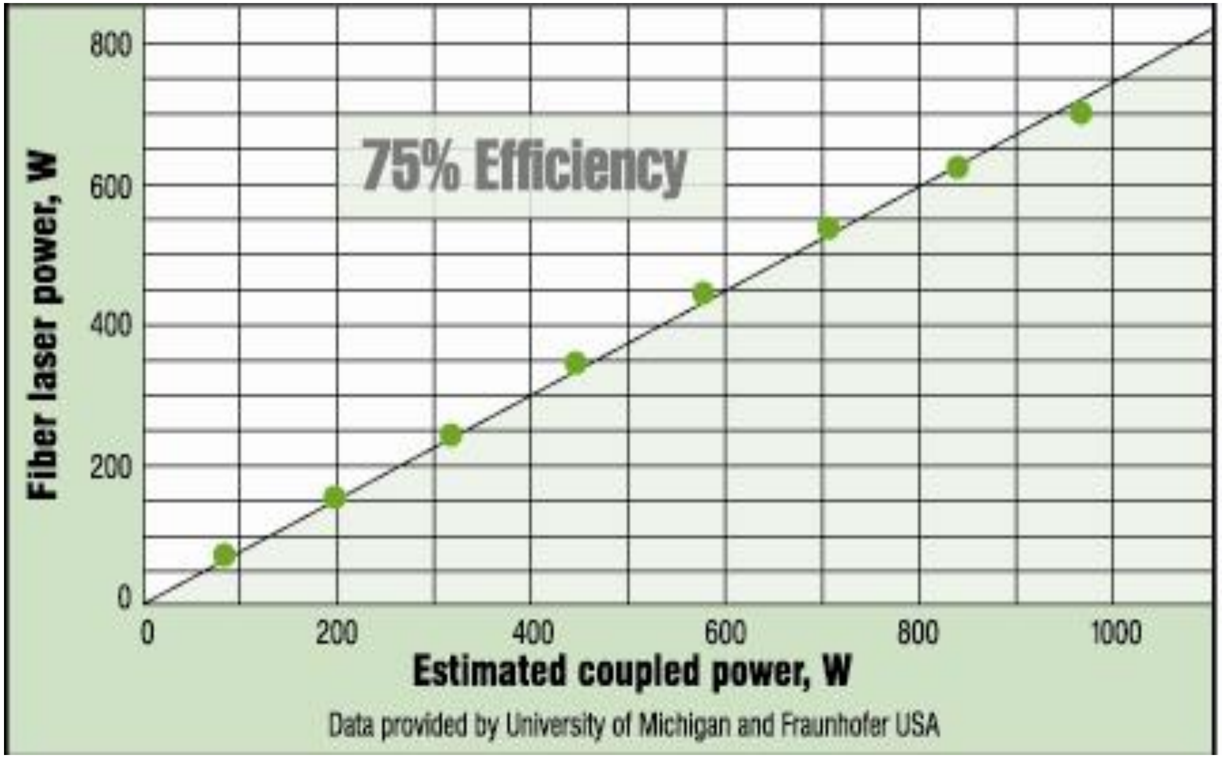
NU0051-01/04

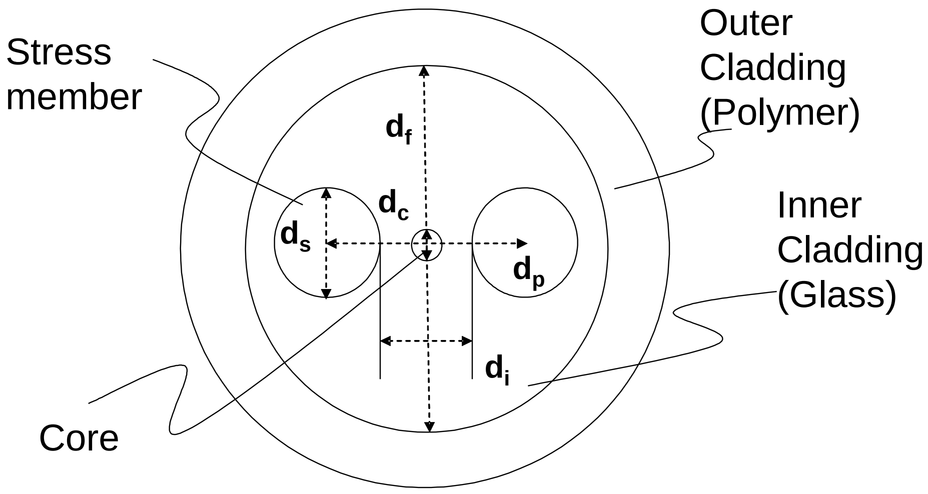
High Power Operation of LMA 20/400 Fiber

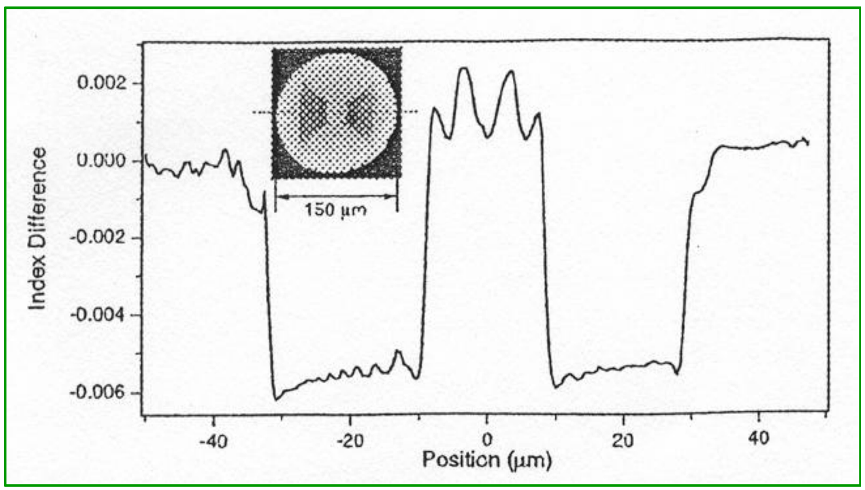
- Tested to > 800 W CW lasing and 1.2 kW pump power
- V# ~3.5 at 1085, so the fiber is double-moded
- Easily delivers single-mode beam quality with ~10 cm coil diameter
- Coiling does not significantly degrade the slope efficiency

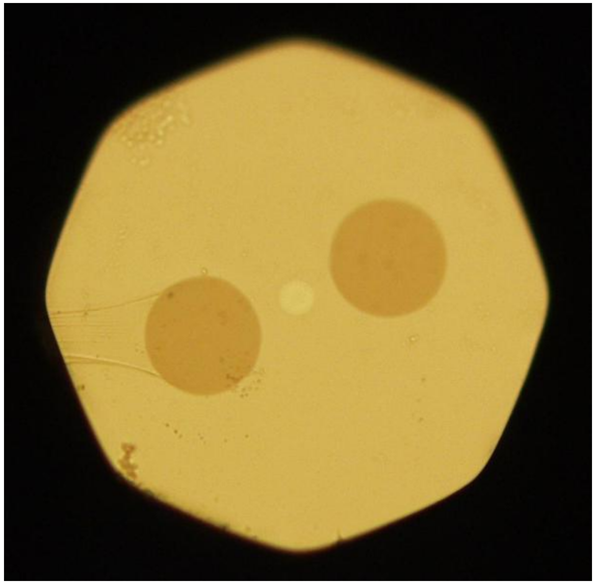


Polarization Maintaining LMA Fibers

- Single polarization needed for
  - power scaling through coherent beam combining
  - non-linear frequency conversion to UV-Vis
- Standard PM-LMA fibers
  - Core sizes:10 to 30 um
  - Clad diameter: 125 to 400 mm



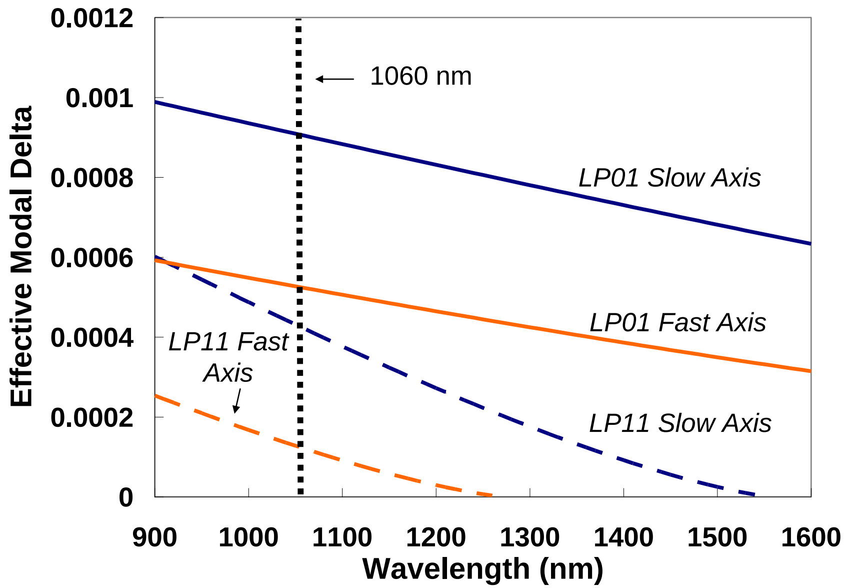


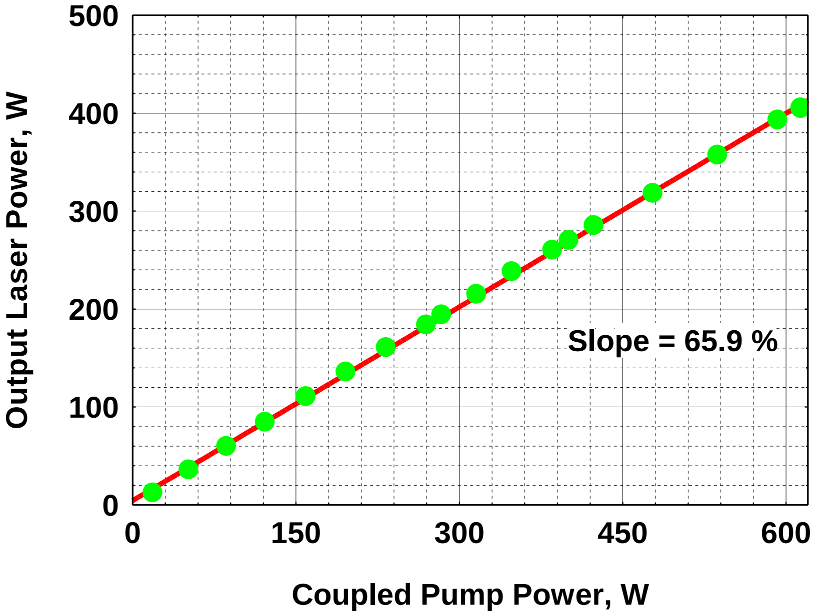


Kliner et al., Optics letters, 26(4), 2001

400 W Polarized Laser

- PLMA-20/400 fiber, B = 3×10^{-4}
- Polarizing Coil (ϕ = 7.5 cm)
  - Coiling removes LP01 Fast and LP11 Fast & Slow
- Applications for linearly polarized SM lasers:
  - Nonlinear frequency conversion
  - Beam combining



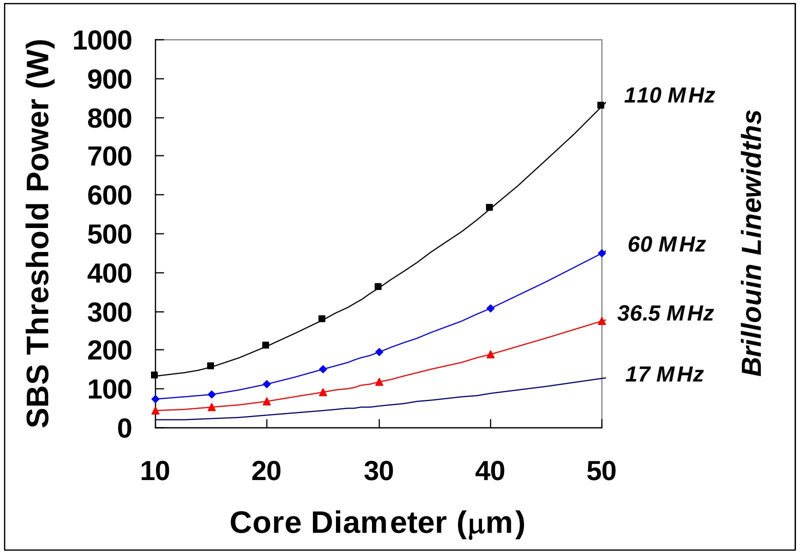


D. Machewirth, V. Khitrov, B. Samson, U. Manyam, K. Tankala, S. Heinemann, C. Liu and A. Galvanauskas, OFC 2005

Limitation to LMA Designs?

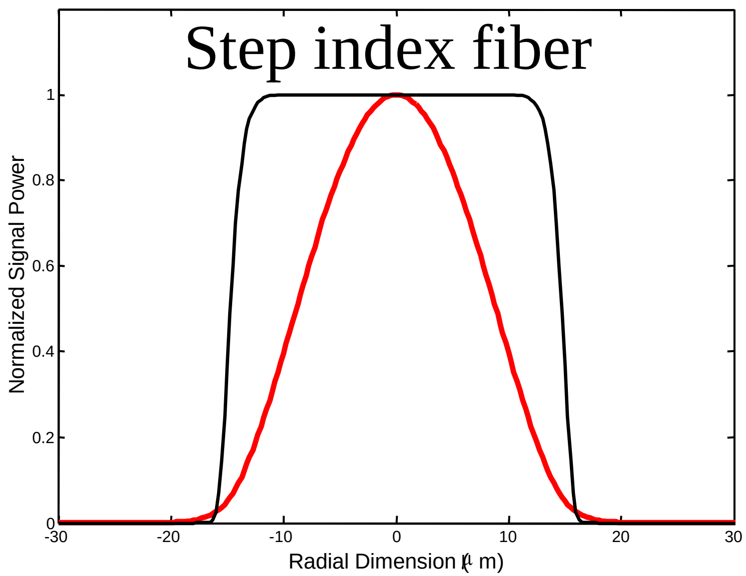
Φcore (μm)	5	20	30	50
NA	0.151	0.06	0.062	0.061
Modeled Mode Field Diameter (1064 nm)	5.77	17.76	23.28	35.5
Modeled Overlap Integral (1064 nm)	0.54	0.72	0.81	0.86
1064 nm abs Estimate (dB/m)	7.18	6.57	7.75	6.71
L (m): 915 nm pump	25.5	25	4.5	4
Threshold Power (W): 915 nm pump	38.9	338.2	676	1363.4
L (m): 975 nm pump	7.7	7.6	1.4	1.2
Threshold Power (W): 976 nm pump	38.9	338.2	736	1613.2

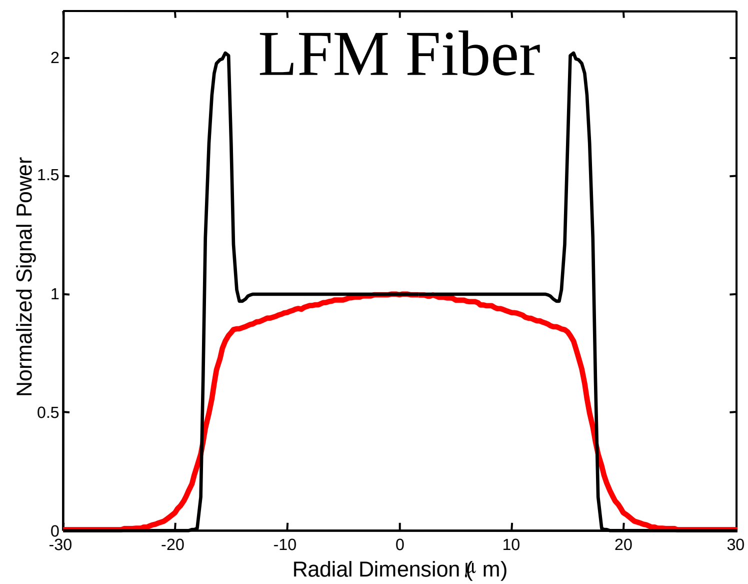
- Excellent beam quality achieved with 50 μm in labs
- Are such fibers suitable for real products?



Power Scaling with Novel Waveguide Designs

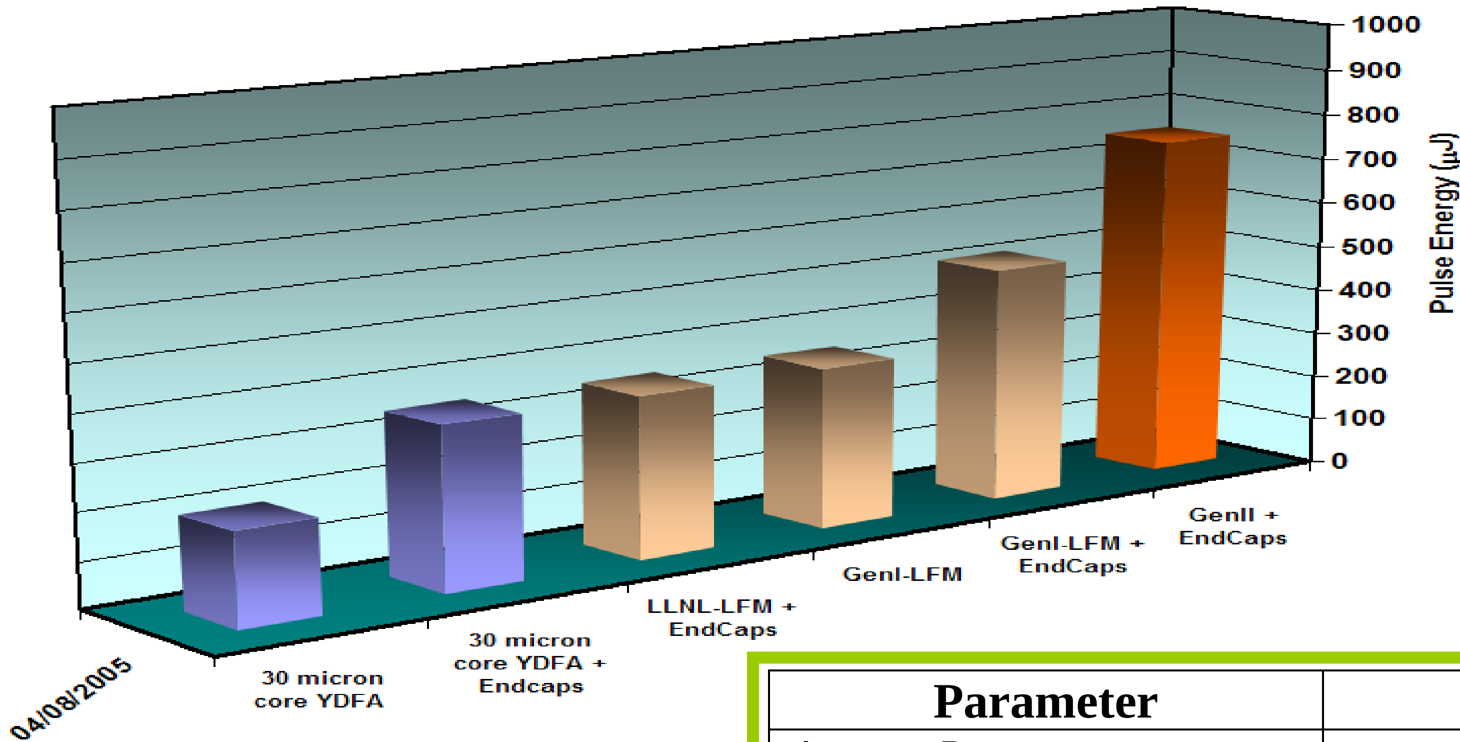
- Non-linear limits can be over come by modifying the fiber index profile
  - eg. LFM by J. Dawson *et al.* at LLNL (CLEO/QELS 2004)
- $A_{eff,\ LFM} \simeq 2.5 * A_{eff,\ control}$ resulting in substantially higher Raman threshold
- Excellent mode quality achieved in LFM fiber





Fiber Development in collaboration with J. Dawson, LLNL (NIF) and W. Torruellas, Fibertek

LFM Power Amplifier Performance



1.5 MW Peak Power!

Data: Courtesy W. Torruellas

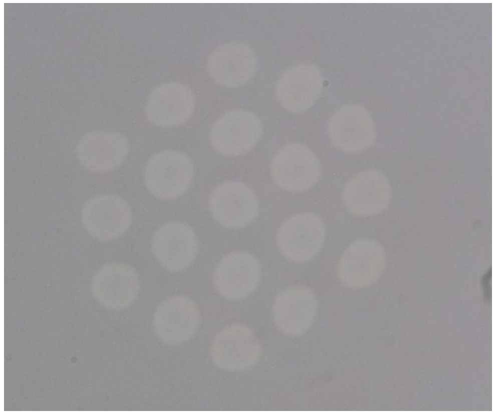
FIBERTEK, INC.

Parameter	Achieved
Average Power	**>10W**
Pulse Energy	**0.75mJ @ 10W**
Repetition Rate	**12.16Kpps @ 10W**
Pulse Duration	**<0. 5ns @ 10W**
M^2	**<1.15 @ 10W**
Spectral Linewidth	**25GHz @ 10W**
SNR Ratio in 0.1nm	**-27dB @10W**

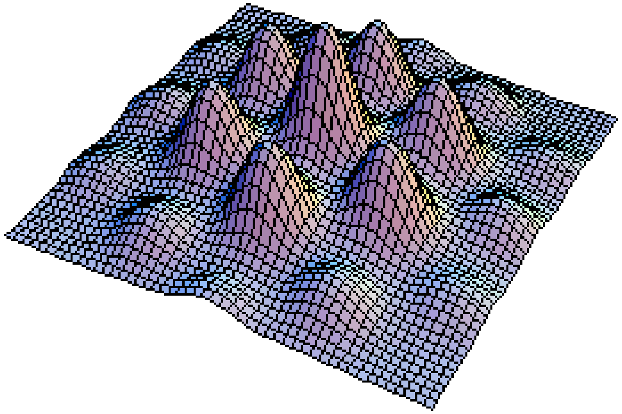
Power Scaling with Multi-Core Fibers

Multi-core fibers offer attractive benefits

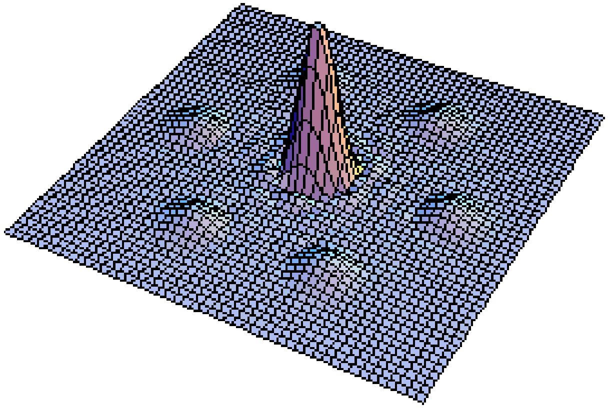
- System integration is easier than multiple fiber amps
- Non-linear coupling of the cores gives an in-phase super-mode
  - 7 core fiber (SDL) is well understood (P. Cheo et al.)
- 19 core fiber (Nufern) has been fabricated and is in test (UoM)



19 core fiber



Near-field

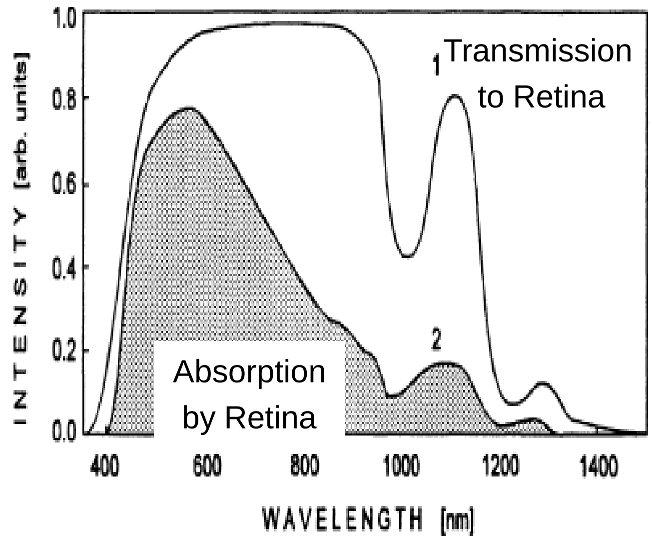


Far-field

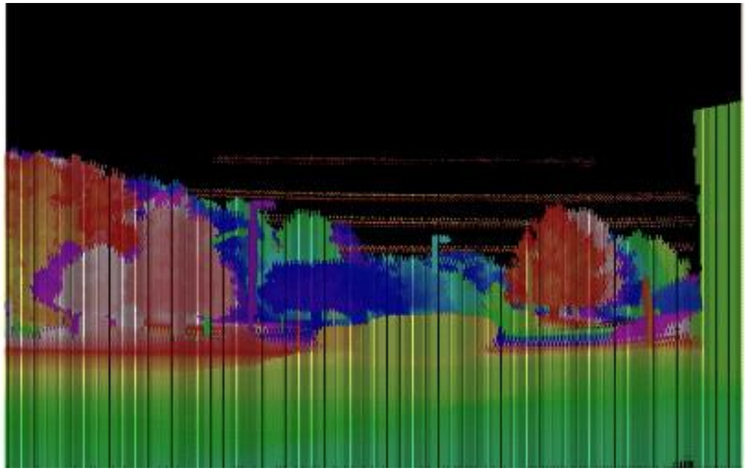
Modeling Data: Courtesy Peter Cheo, PC Photonics

High Power Fibers at Eye Safe Wavelengths

- Eye-safe lasers are critical in areas where human interaction with direct or scattered laser light is likely
- Retinal absorption is 4 orders of magnitude lower at 1.5um vs.1um



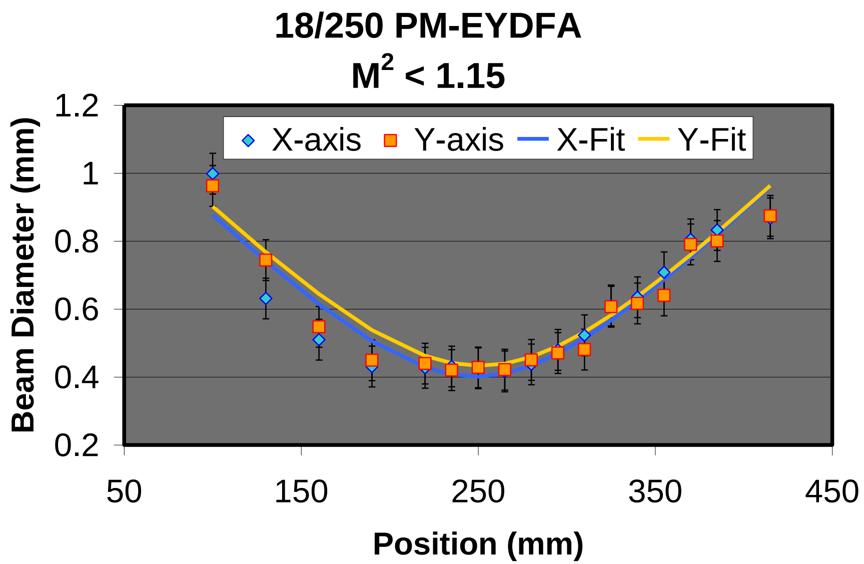
Fiber based LIDAR

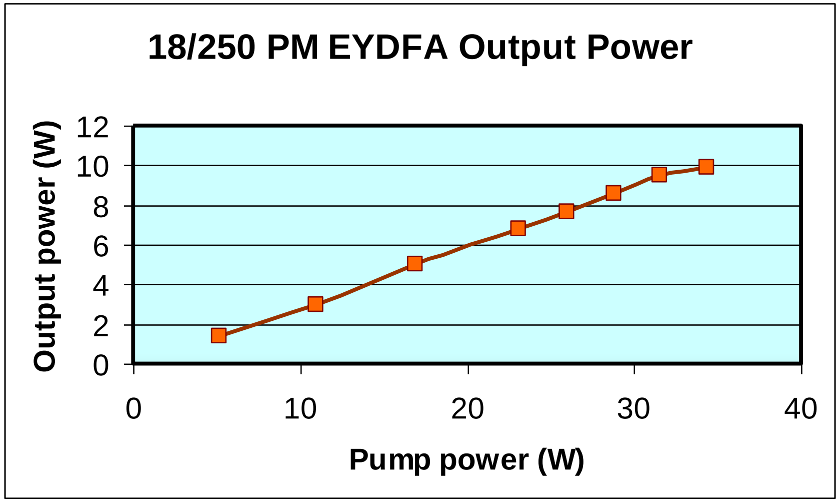


Images: Courtesy W. Torreullas, Fibertek

Er:Yb co-doped fibers (1.55 μm)

- PM-EYDF-18/250 fiber
  - Has delivered ~100 μJ pulses and P_{ave}~10 W
  - 3 ns pulses, peak power > 30 kW (~ 65 J/cm2)
  - Single mode output (M^2 ~ 1.1)
- LMA Er/Yb fibers in development (Funded by AFRL)



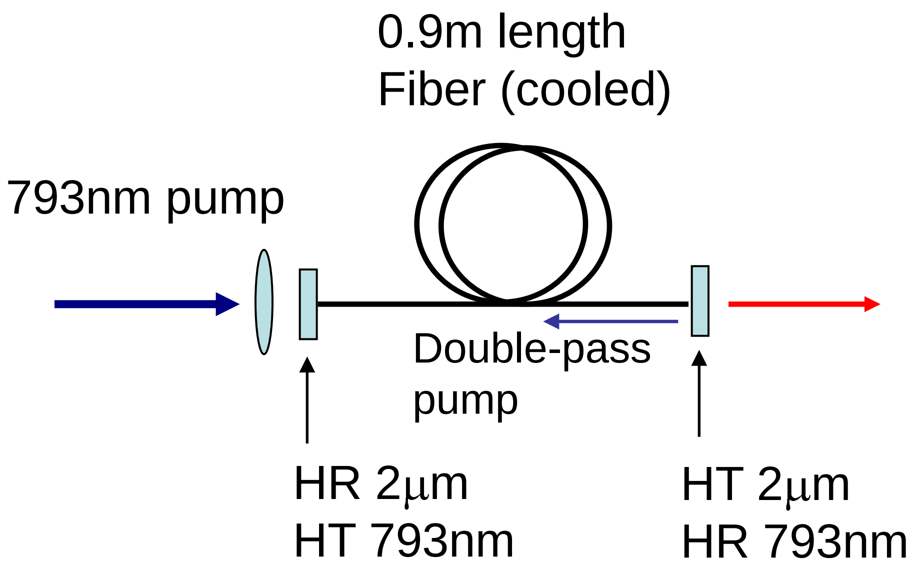


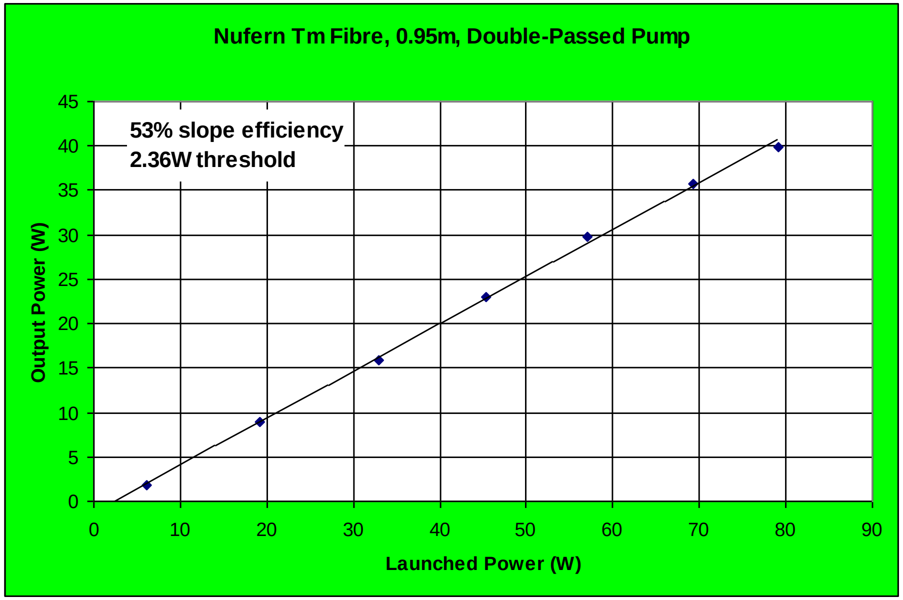
Data: Courtesy W. Torruellas, Fibertek

Y. Chen, B. McIntosh, W. Torruellas, A. Carter, J. Farroni and K. Tankala, PW 2005

Tm-doped fibers (2 μm)

Australian Government
Department of Defence
Defence Science and
Technology Organisation



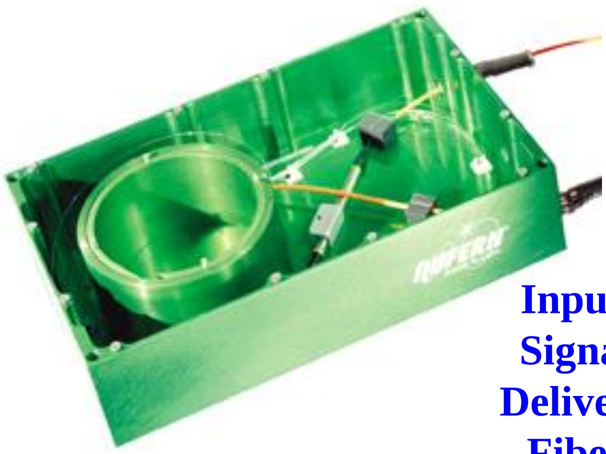


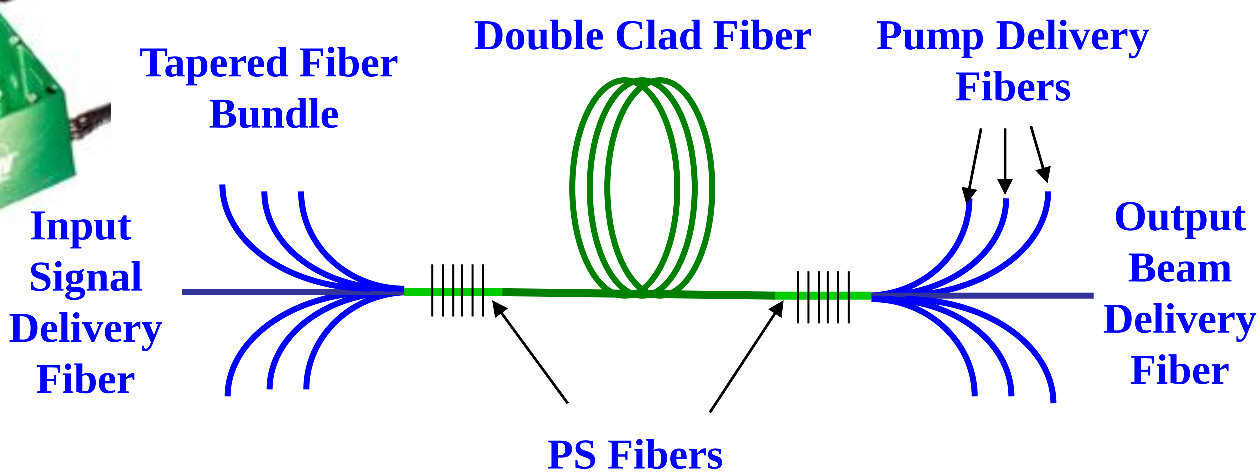
Data: Courtesy Gavin Frith, DSTO

- High efficiency ~60% pump conversion
  - Lasing around ~1970nm pump at 793nm
  - Silica glass composition is optimised for high efficiency
    - "2-for-1 process" by exploiting Tm-ion cross relaxation process
- 40 W CW output achieved with 793 nm pumping

Monolithic Fiber Laser/Amplifier Modules

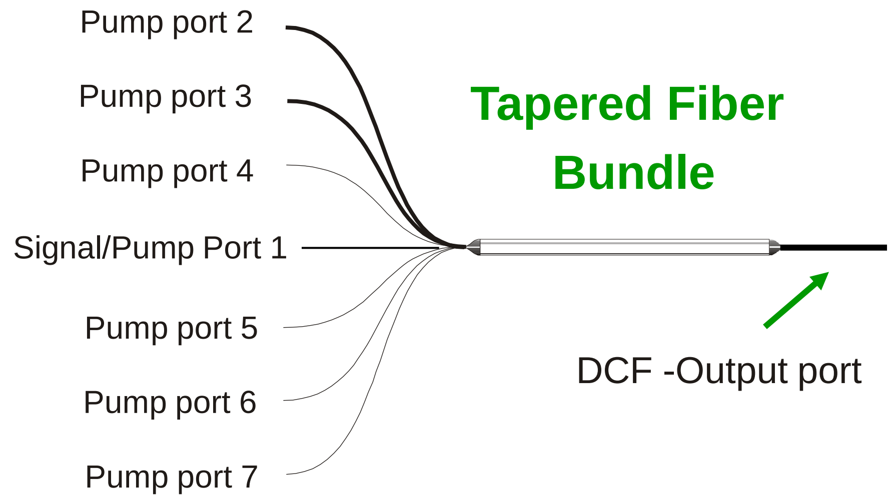
- “All fiber” devices are compact, robust and reliable
- Higher power devices are currently being commercialized
  - High Brightness diodes
  - High power components (Pump combiners, Bragg gratings)
  - Passive fibers (pump and signal delivery, photosensitive fibers)
  - Splicing and packaging technologies





High Power Pump Combiners

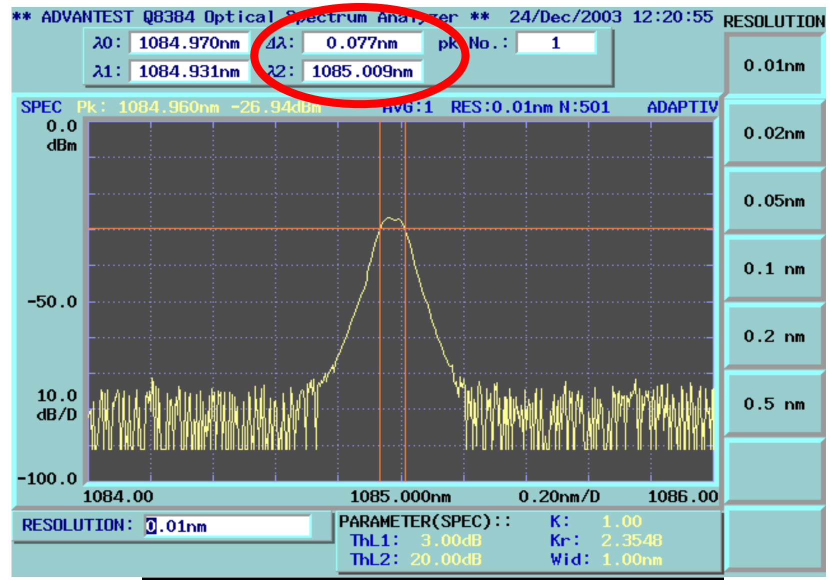
- High power multi-mode couplers are now widely available in various configurations
- Allow great flexibility in choosing the diode pump technology for each application

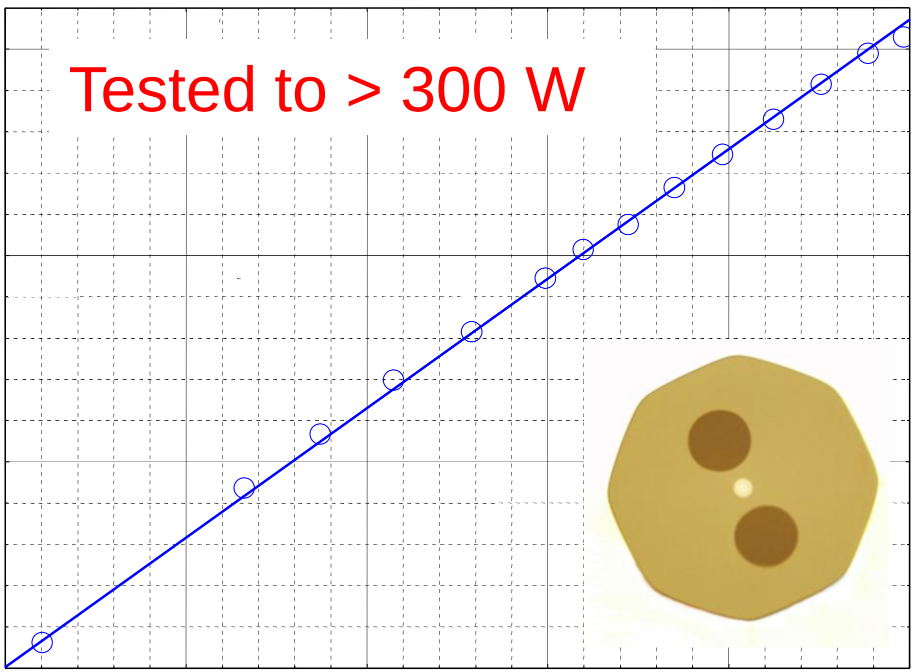


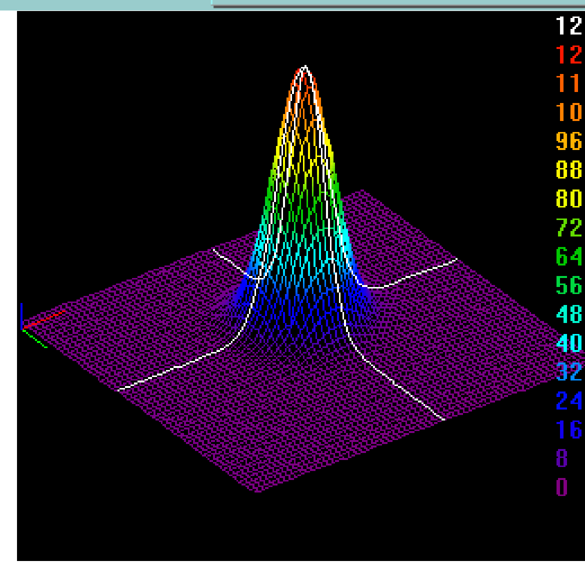
Input Fibers to Combiner (core/clad)	Output Fiber (diameter and NA)	Typical (max) Number of Input fibers	Diode Pump Technology	Typical Power/Leg	Total Pump Power
105/125 0.22NA	400µm 0.46NA	19 (37)	pigtailed single emitter	3-5 W	95W (180W)
200/220 0.22NA	400µm, 0.46NA	7 (7)	fiber coupled diode bars	10-25W	70-175W
400/440 0.22NA	400µm, 0.46NA	3 (3)	Fiber coupled bars and stacks	30-200W	90-600W

LMA Fiber Bragg Gratings

- Photosensitive LMA fibers compatible with Yb-doped LMA fibers developed
- LMA Gratings available (1030 to 1120 nm)

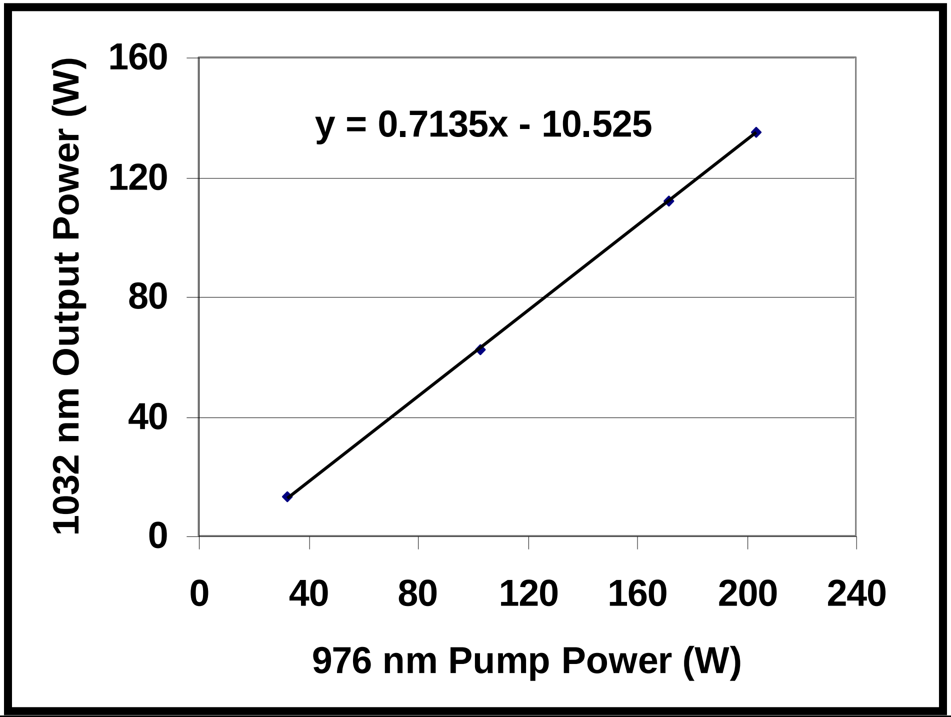


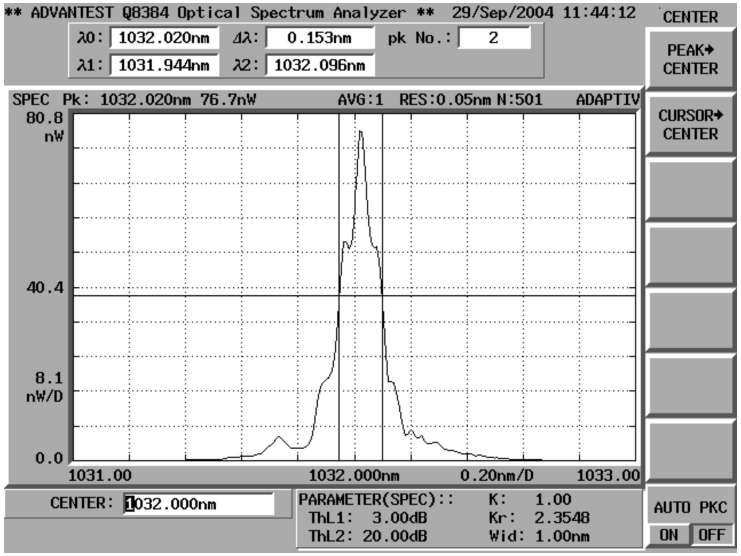




High power 1030nm Laser (20/400)

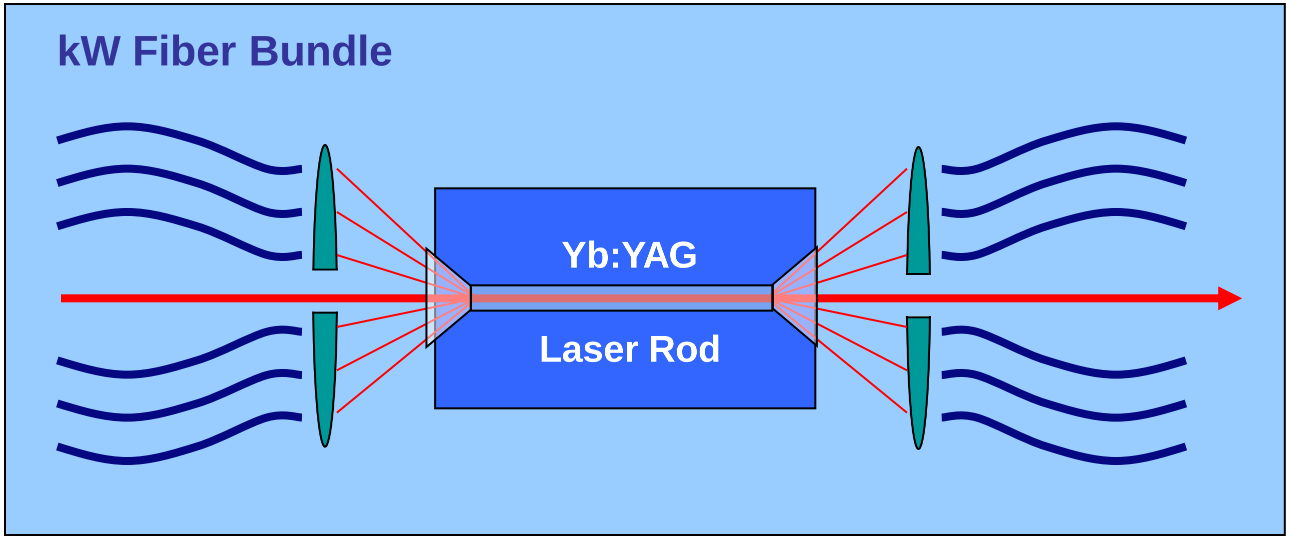
- Grating based cavities are efficient and robust (no realignment)
- Extra degree of wavelength control and line width control
  - ➢ Critical for non-linear frequency conversion and pumping solid state lasers



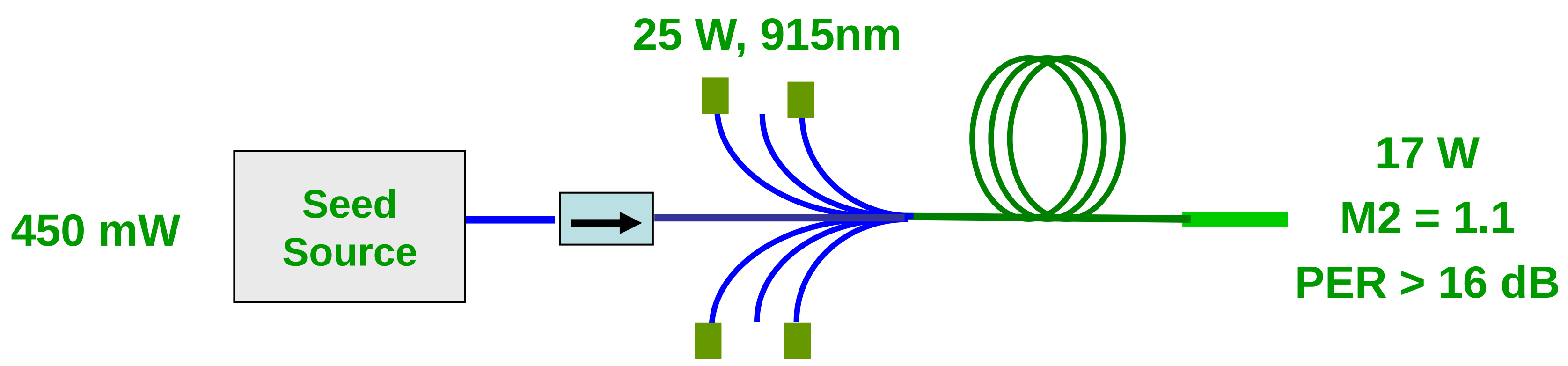


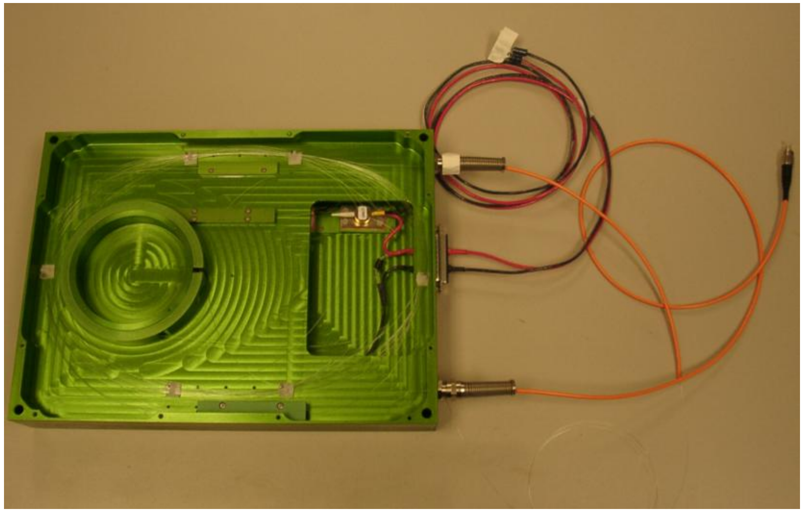
Fiber laser as pump source for Yb:YAG

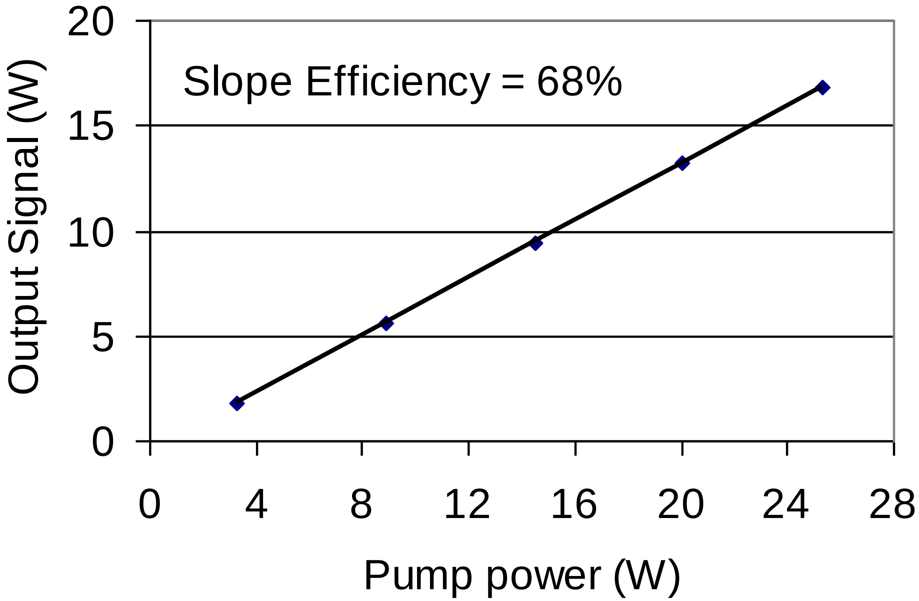
- Concept for very high average power laser systems
- Anti-Stoke fluorescence cooling laser offsets heat generation
- Fiber lasers used as high brightness pump sources
  - Use multiple fiber lasers to pump 1050nm laser
  - Minimizes quantum defect by pumping at 1030nm
  - High brightness pumps permit low cross section host



Low Power PM Amplifiers (15/130 fiber)

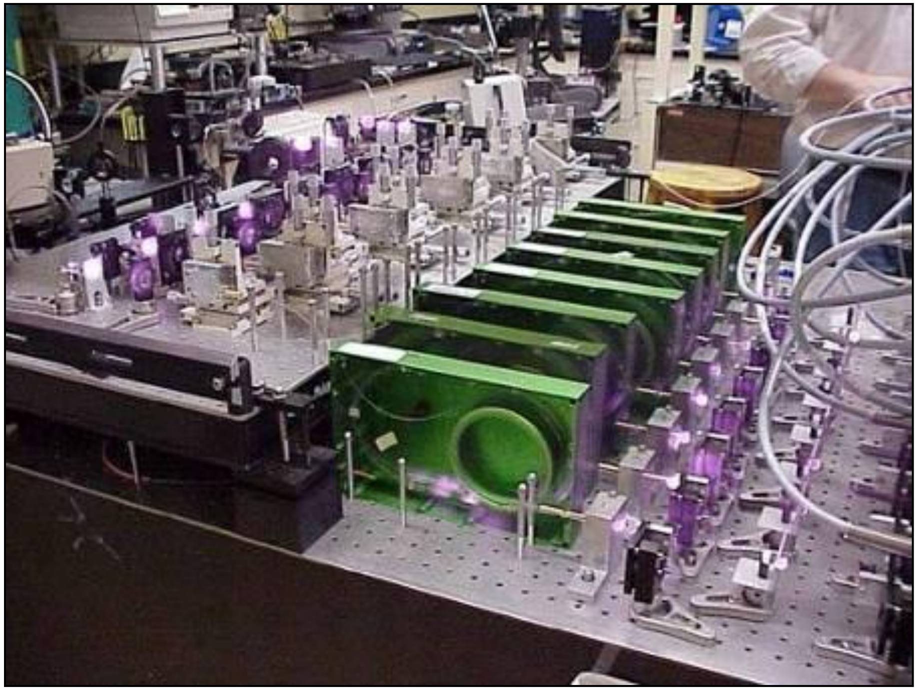






Power Scaling to > 25kW

- Beam combining of individual fiber lasers and amplifiers
  - Coherent Beam Combining
  - Spectral Beam Combining
  - Phase Locking of Lasers
- Beam combining requires
  - Narrow line width
  - linear polarization
  - Good beam quality ($M^2 = 1$)
- Next Steps
  - PM Amplifiers
  - 500 -1000 W Amplifier Units



Courtesy Monica Minden, Hughes Research Lab

Summary

- Fiber laser have intrinsic advantages over conventional Solid State and CO_2 lasers
- LMA DC Fibers have enabled high power operation
  - Kilowatt level CW powers
  - Megawatt level peak powers (nanosecond pulses)
- Broad range of monolithic CW and pulsed fiber laser and amplifier modules are being developed for
  - Materials processing
  - Lidar/Ladar systems
  - Laser Weapon Systems

Thank You

Acknowledgements

D. Kliner & J. Koplow, SNL

W. Torruellas, Fibertek Inc

G. Frith, DSTO

M. Minden, HRL

S. Bowman, NRL

A. Galvanauskas, U. of Michigan

P. Cheo, PC Photonics

J. Dawson, LLNL

Francois Gonthier, ITF

Air Force Research Labs

Nufern Colleagues