High power Tm:silica fiber lasers: current status, prospects and challenges

Presentation TF2.3
Tech Focus Talk
Novel Fibre Lasers and Applications
CLEO/Europe and Lasers in Manufacturing
May 24, 2011

Peter Moulton
Q-Peak, Inc.

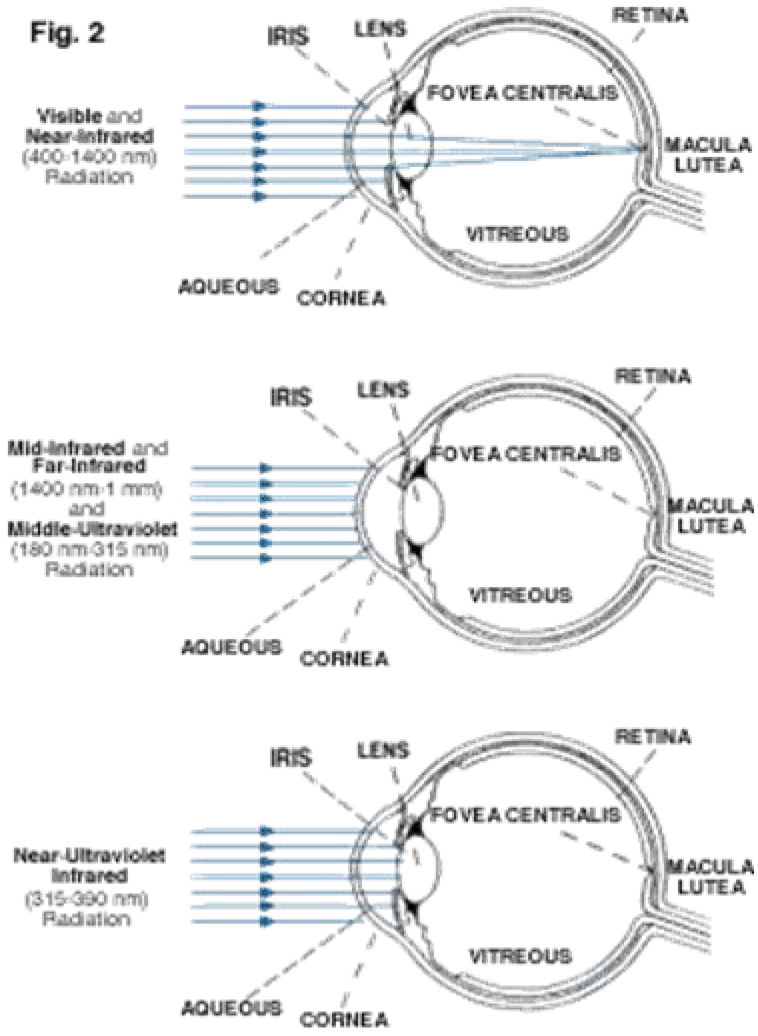
Outline

- Fundamentals of Tm:fiber lasers
- Spectroscopy studies
- Laser results
- Challenges/Prospects
- Summary

Credits

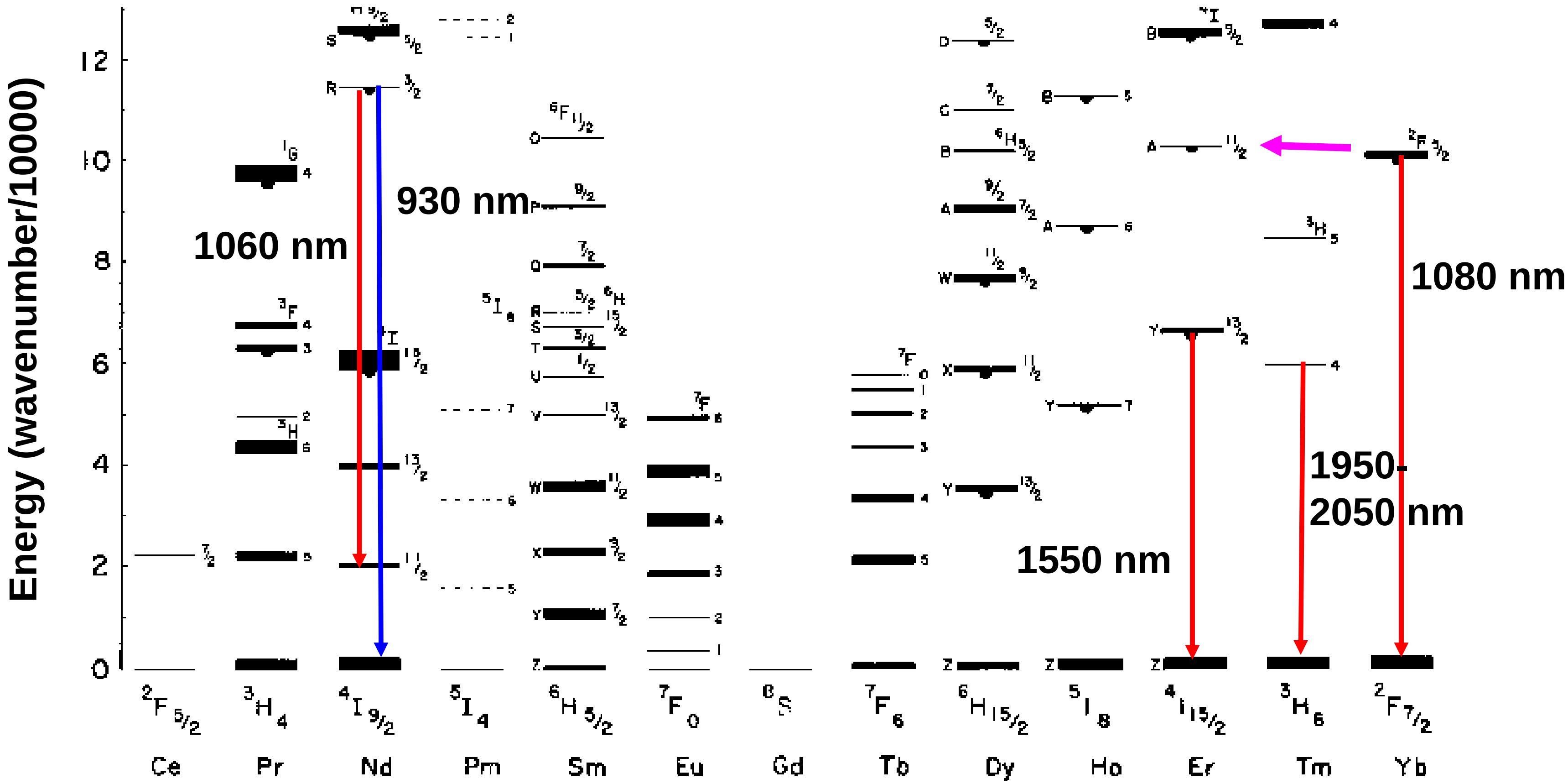
- **Q-Peak, Inc.**
  - **Glen Rines, Evgueni Slobodtchikov, Kevin Wall, Sam Wong**
- **Nufern, Inc.**
  - **Thomas Ehrenreich, Ryan Leveille, Imtiaz Majid, and Kanishka Tankala**
- **Funding**
  - **HEL/JTO**

Relative eye safety is obtained for > 1400-nm wavelengths

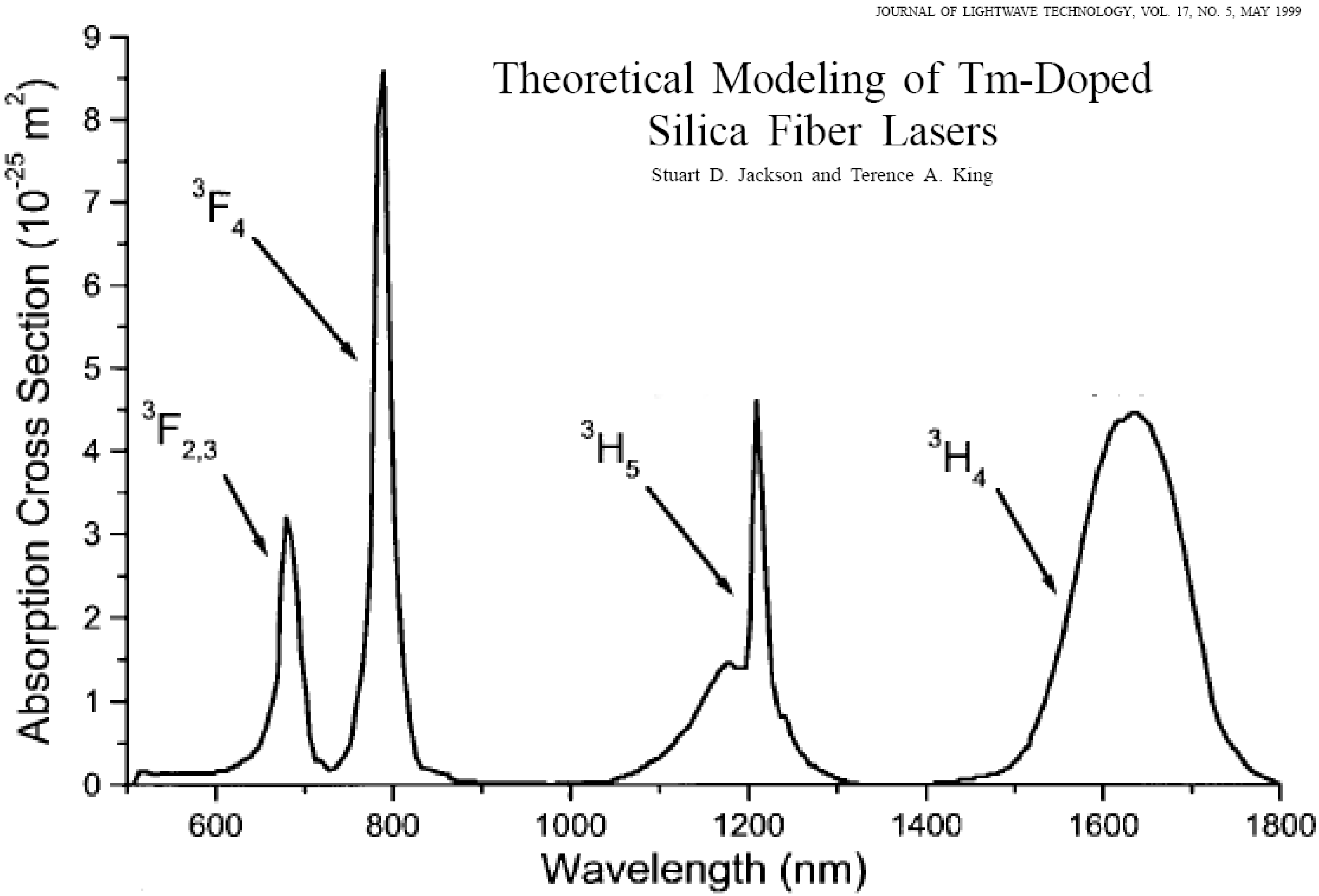


Retinal focusing can increase the power density by 10^5

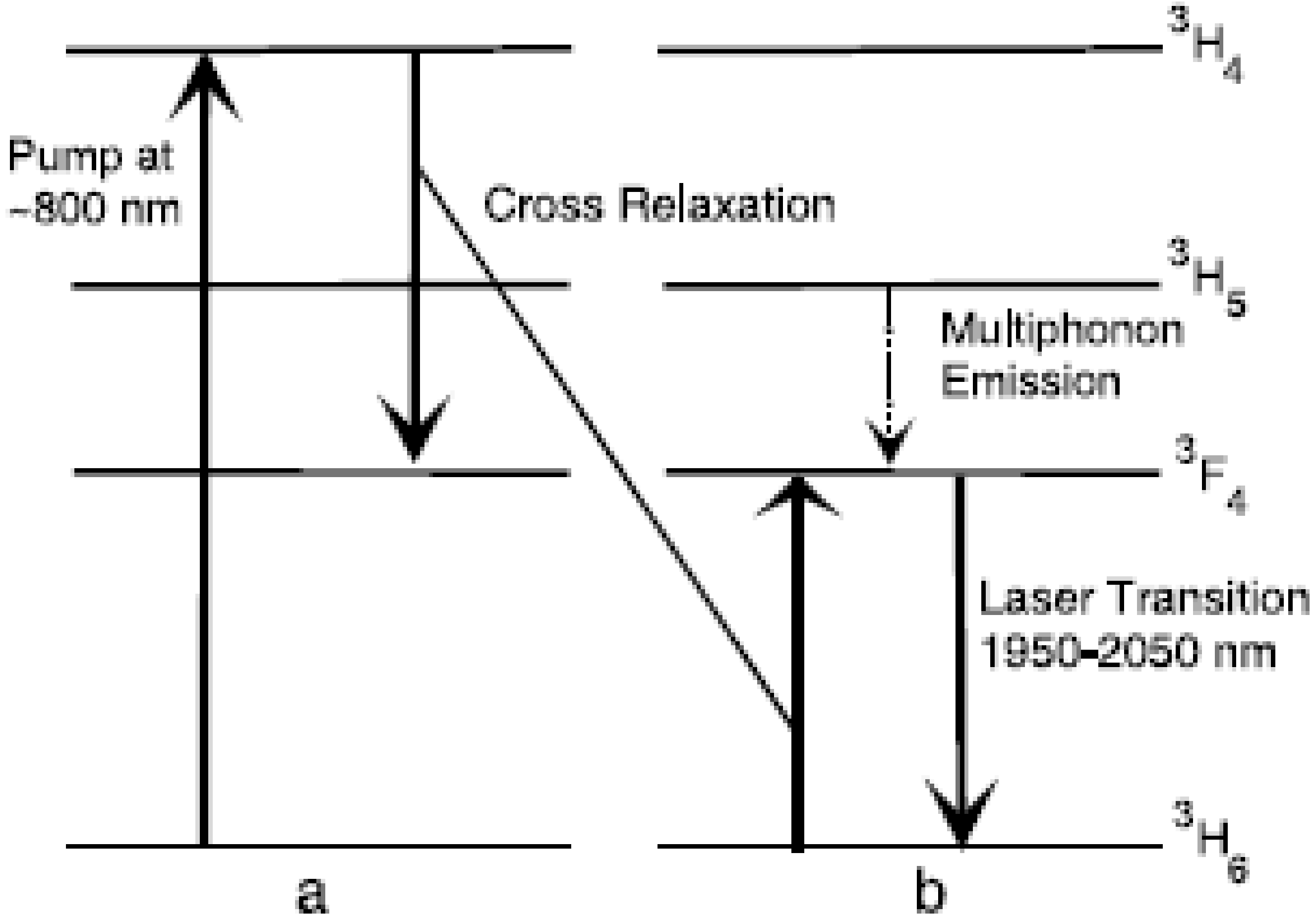
Rare-earth laser transitions can provide eyesafe wavelengths in fibers



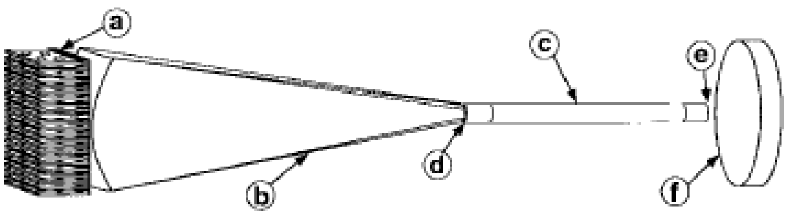
Tm-doped fibers show a number of pump bands

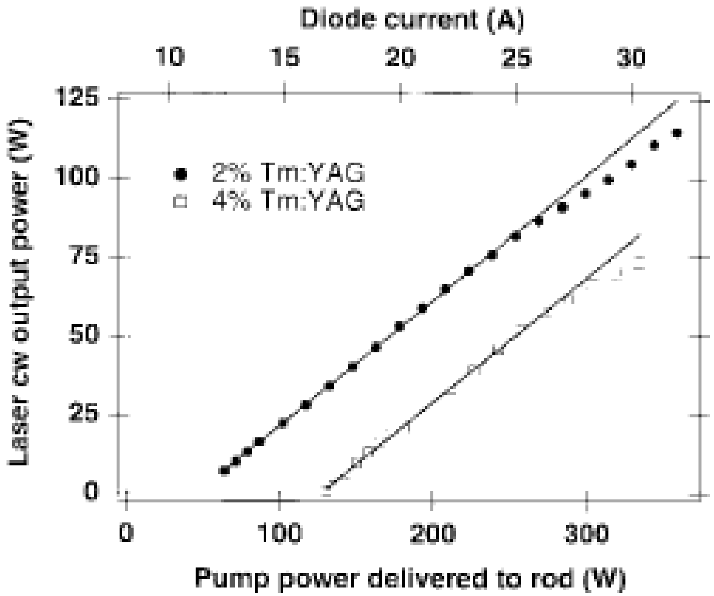


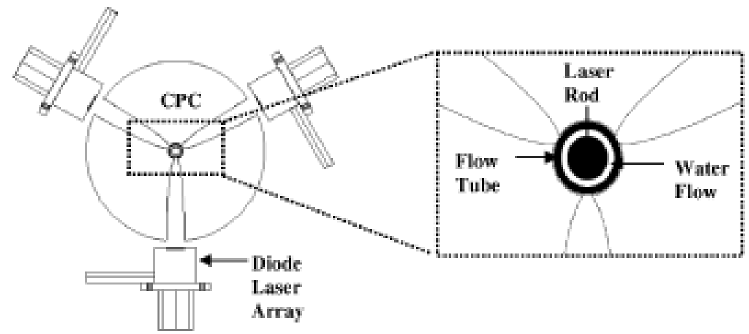
Tm-ion cross relaxation allows excitation of two upper laser levels for one pump photon

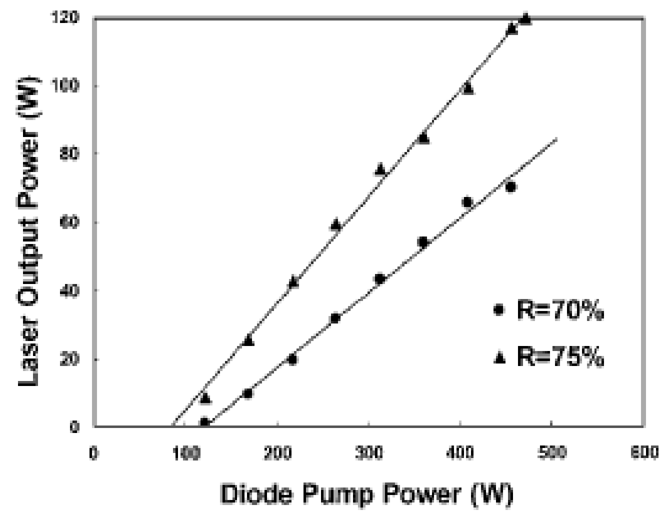


Prior work with Tm:YAG lasers showed high efficiency with 79X pumps





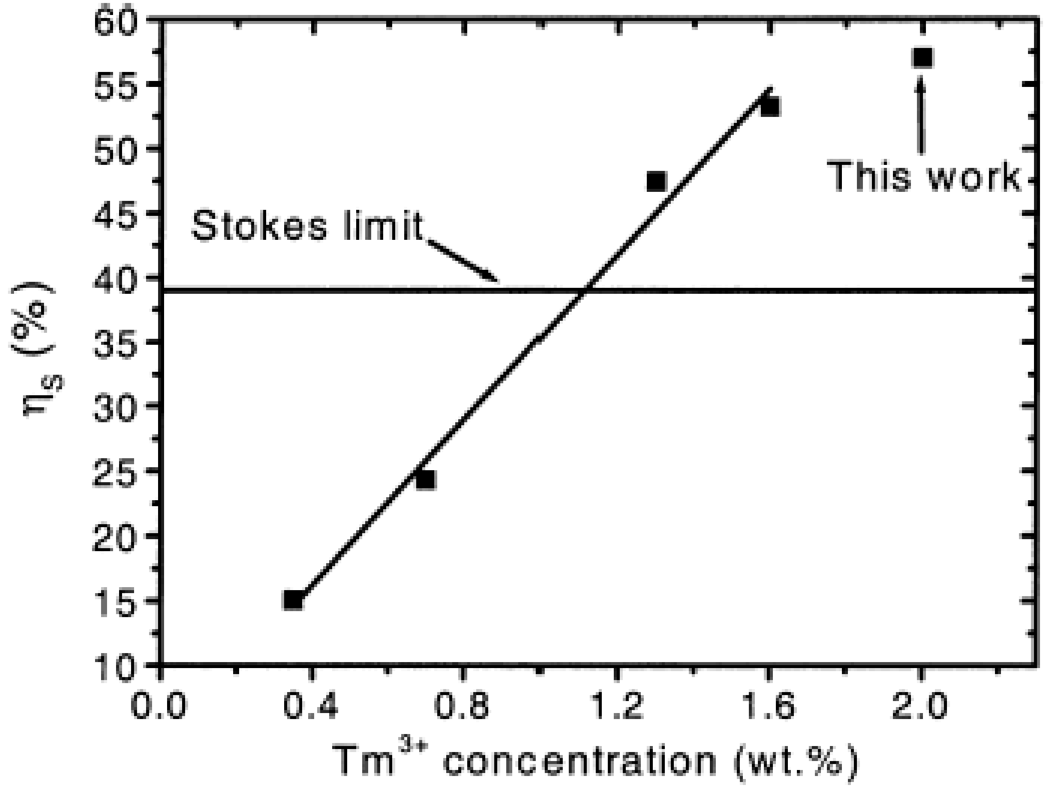




E.C. Honea, R.J. Beach, S.B. Sutton, J. A. Speth, S.C. Mitchell, J.A. Skidmore, M.A. Emanuel, and S.A. Payne, "115-W Tm:YAG Diode-Pumped Solid-State Laser," J. Quantum Electron. **33**, 1592 (1997).

K. S. Lai, P. B. Phua, R. F. Wu, Y. L. Lim, E. Lau, S. W. Toh, B. T. Toh, and A. Chng, "120-W continuous-wave diode-pumped Tm:YAG laser ," Opt. Lett. **25**, 1591-1593 (2000).

790-nm pumping: silica fiber efficiencies exceed the quantum limit at high [Tm]

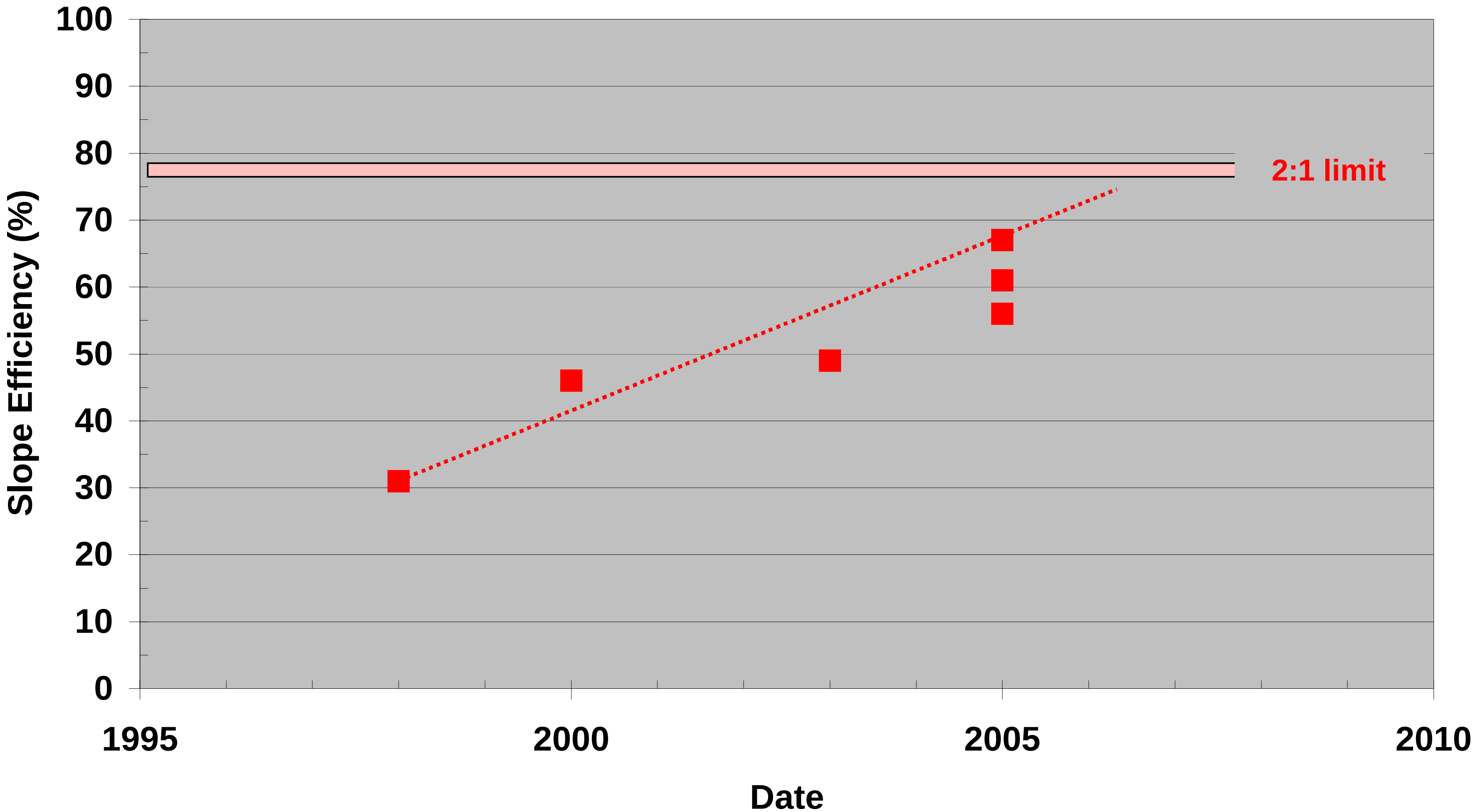


2192 OPTICS LETTERS / Vol. 28, No. 22 / November 15, 2003

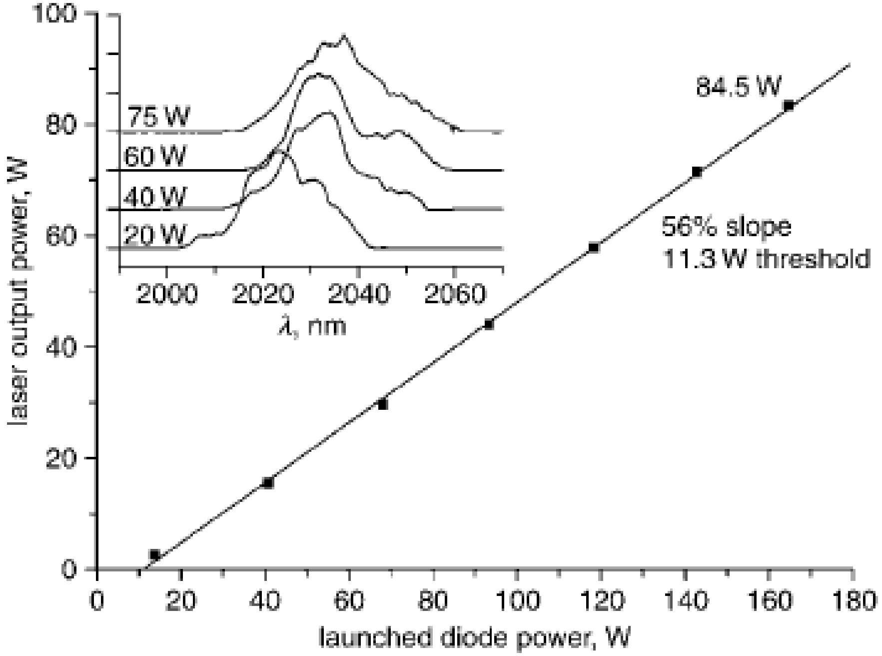
Power scaling method for 2-μm diode-cladding-pumped Tm^{3+}-doped silica fiber lasers that uses Yb^{3+} codoping

Stuart D. Jackson

Advances in Tm-doped fiber-laser efficiencies show levels approaching Yb fibers



Power levels approaching 100 W in 2005 suggested further scaling



G. Frith, D.G. Lancaster and S.D. Jackson, “85 W Tm3+-doped silica fibre laser,” Electron. Lett. 41, 1207 (2005).

D.Y. Shen, J.L. Mackenzie, J.K. Sahu, W.A. Clarkson and S.D. Jackson, “High-power and ultra-efficient operation of a Tm3+- doped silica fiber laser,” OSA Topical Meeting on Advanced Solid State Photonics, 2005 (Vienna), Paper MC-6.

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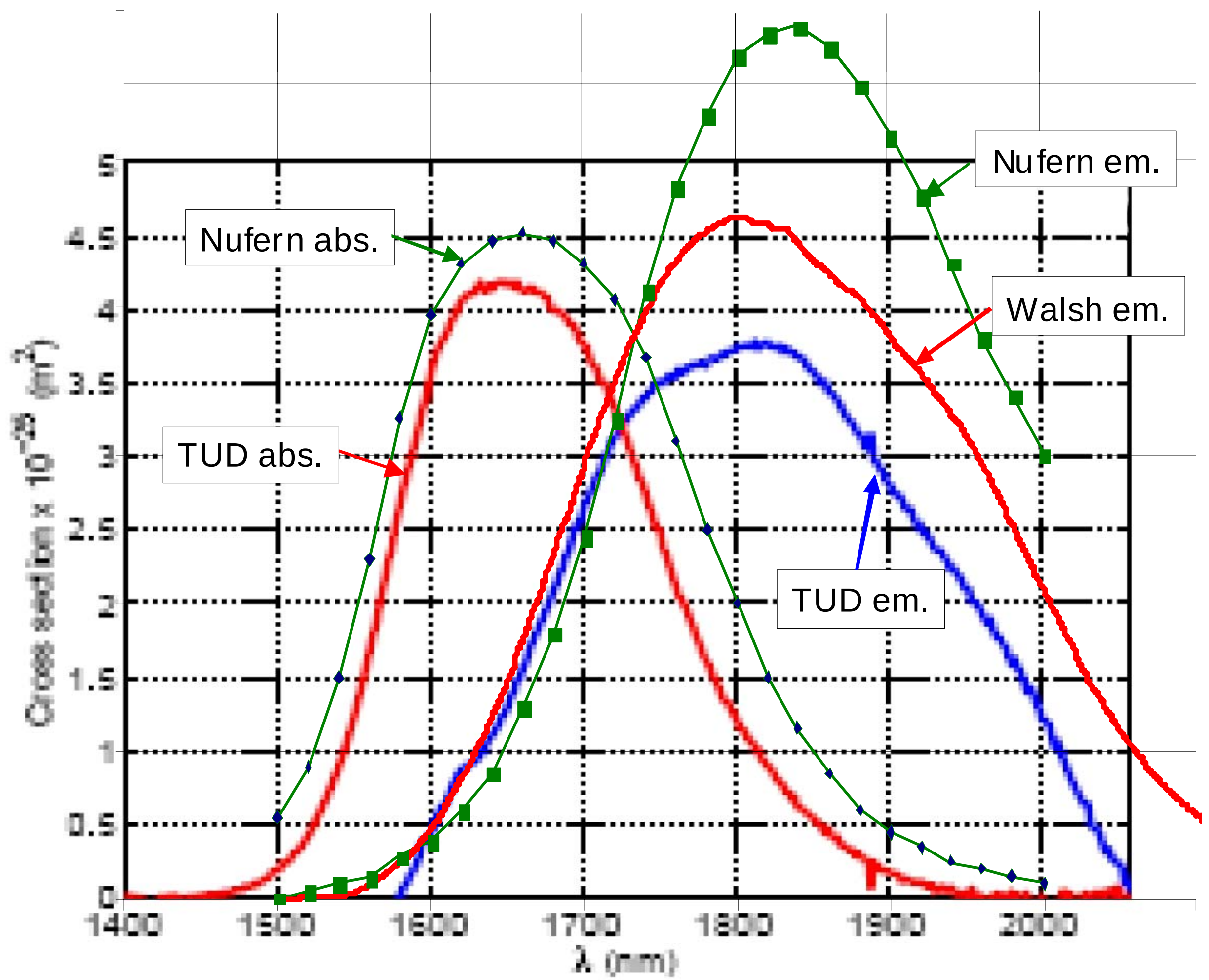
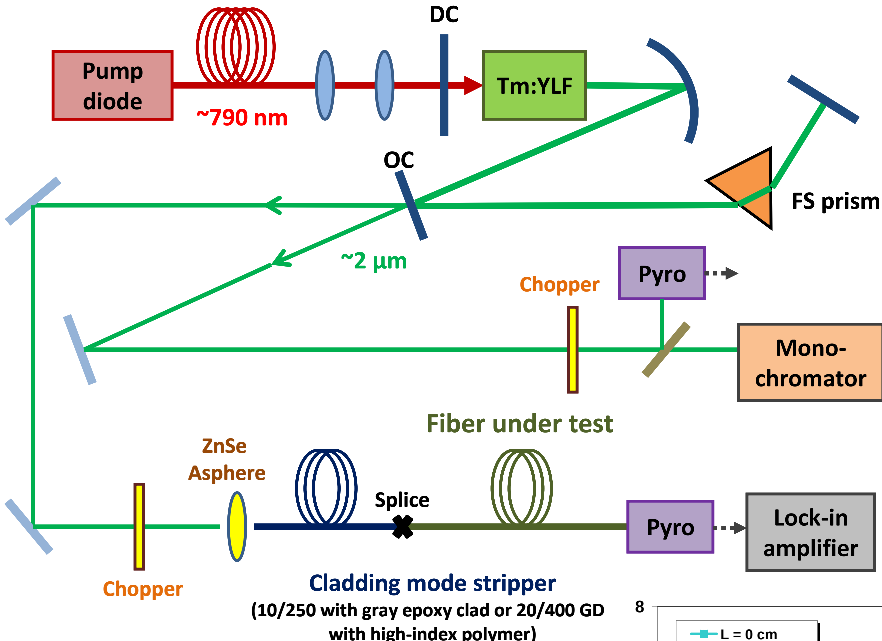
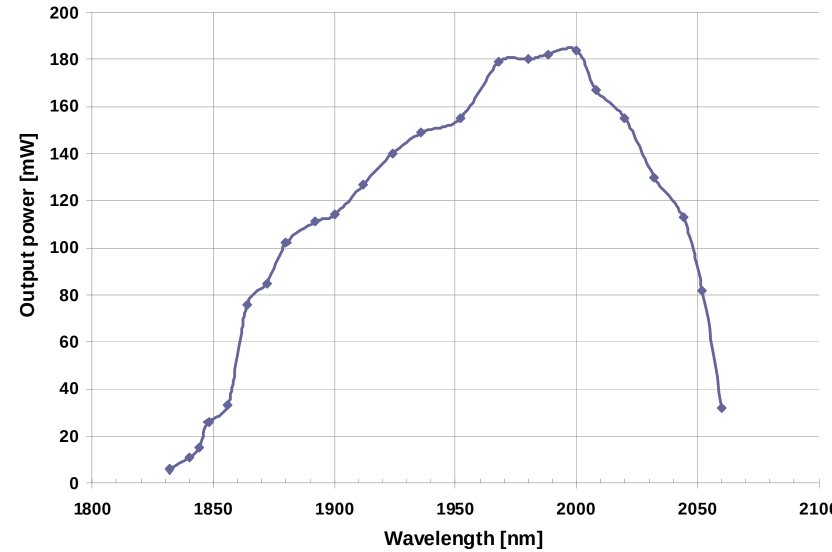
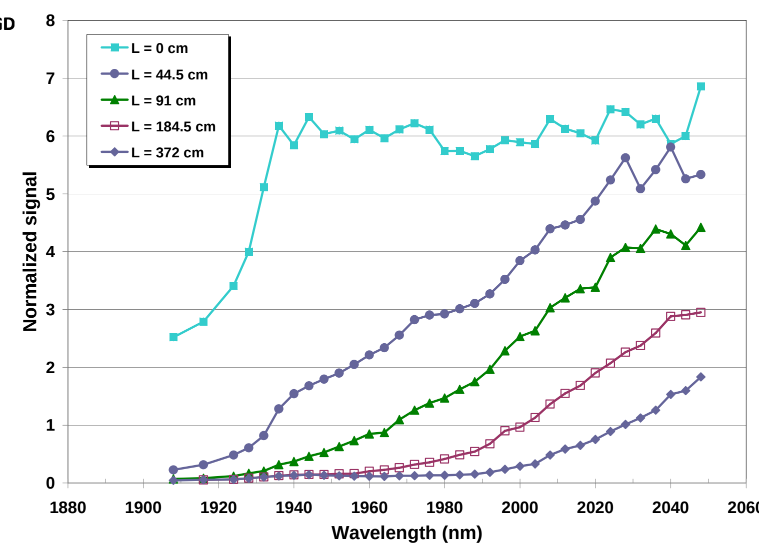
Conflicting data on absorption and emission of Tm:silica



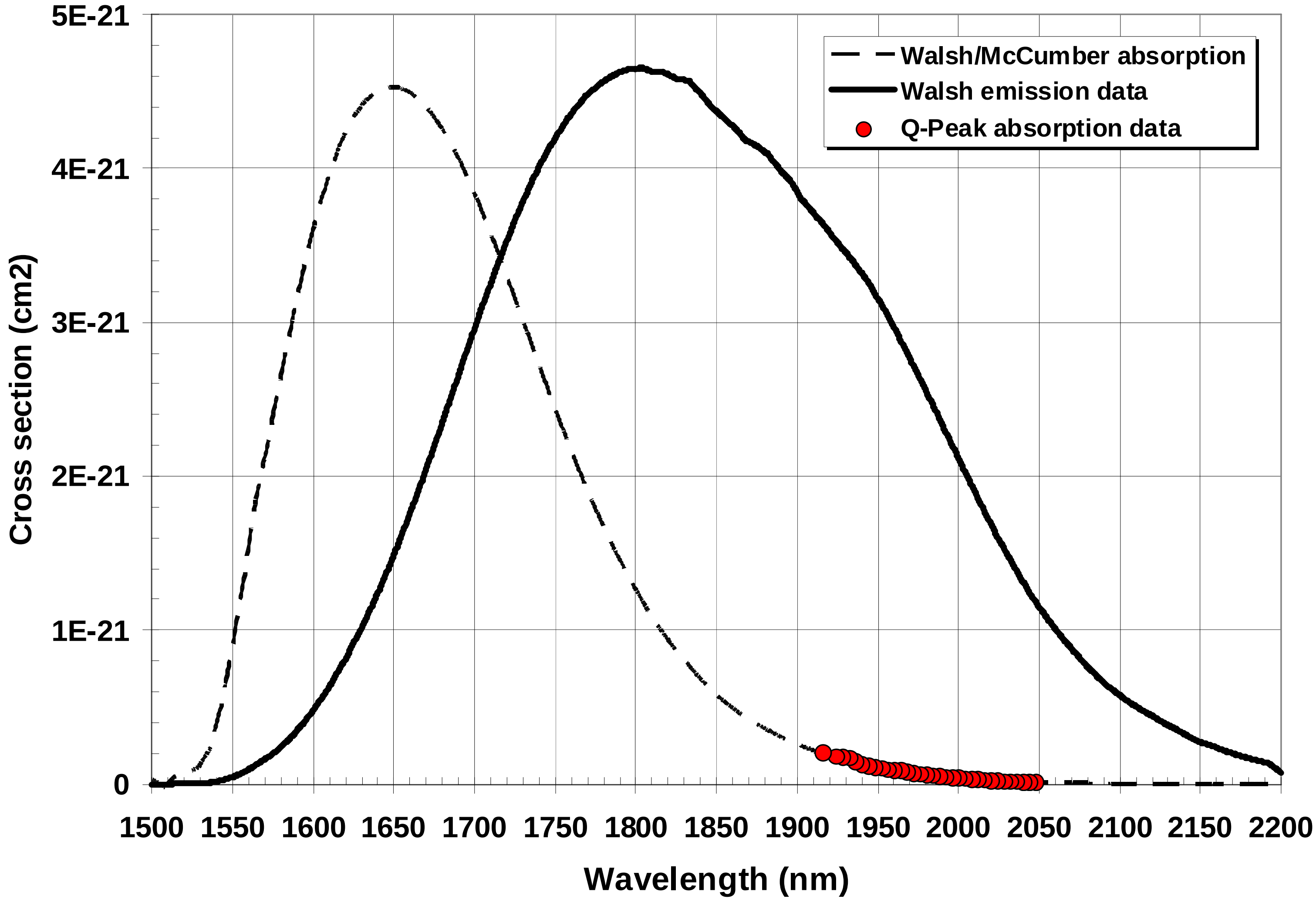
Fiber absorption measurement system



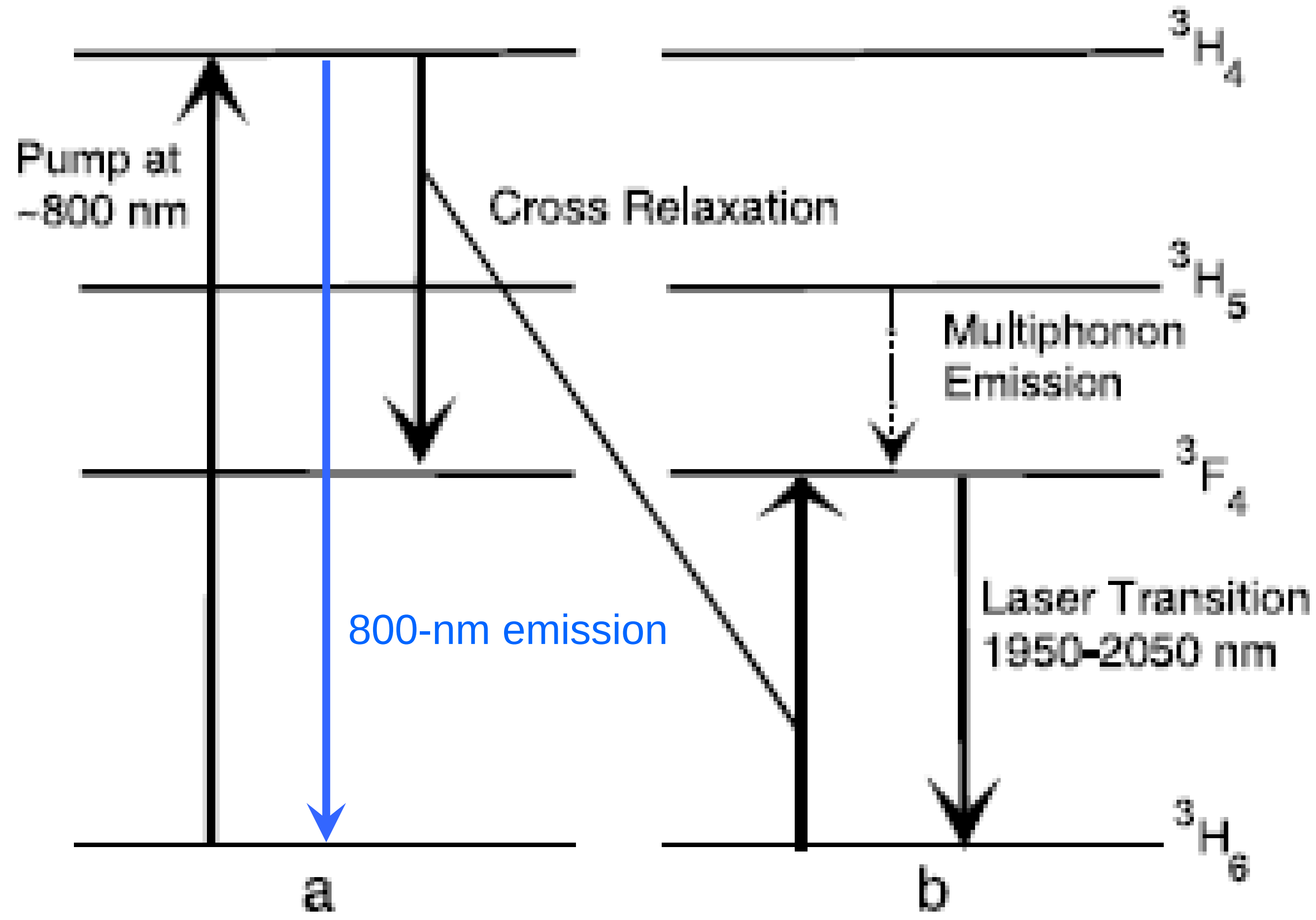




“Best” choice of absorption and emission data



Dynamics measurements of Tm:silica employed ns-pulsed Ti:sapphire laser



Decay data for $^3F_4$ (upper laser) level shows two-lifetime dynamics

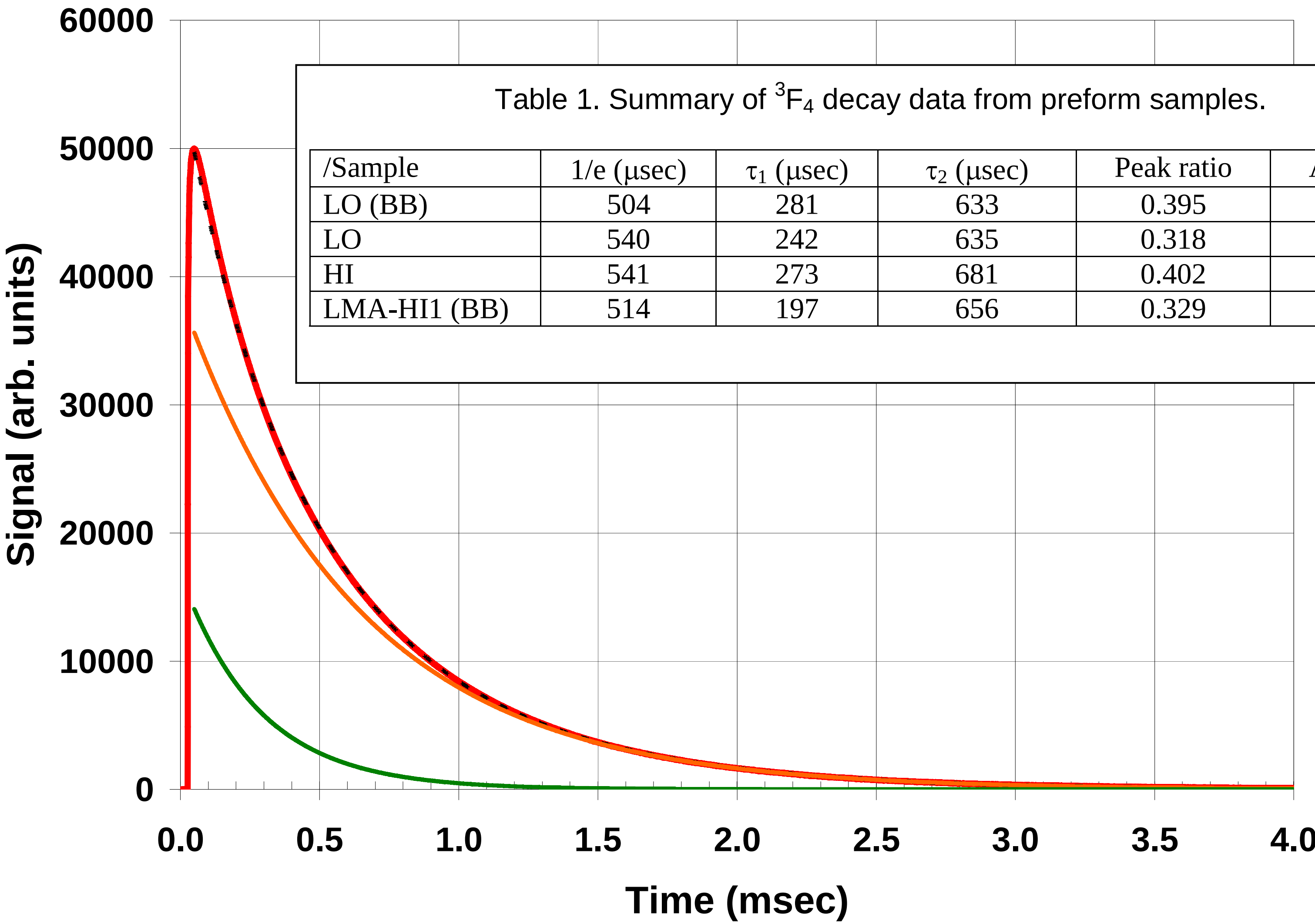
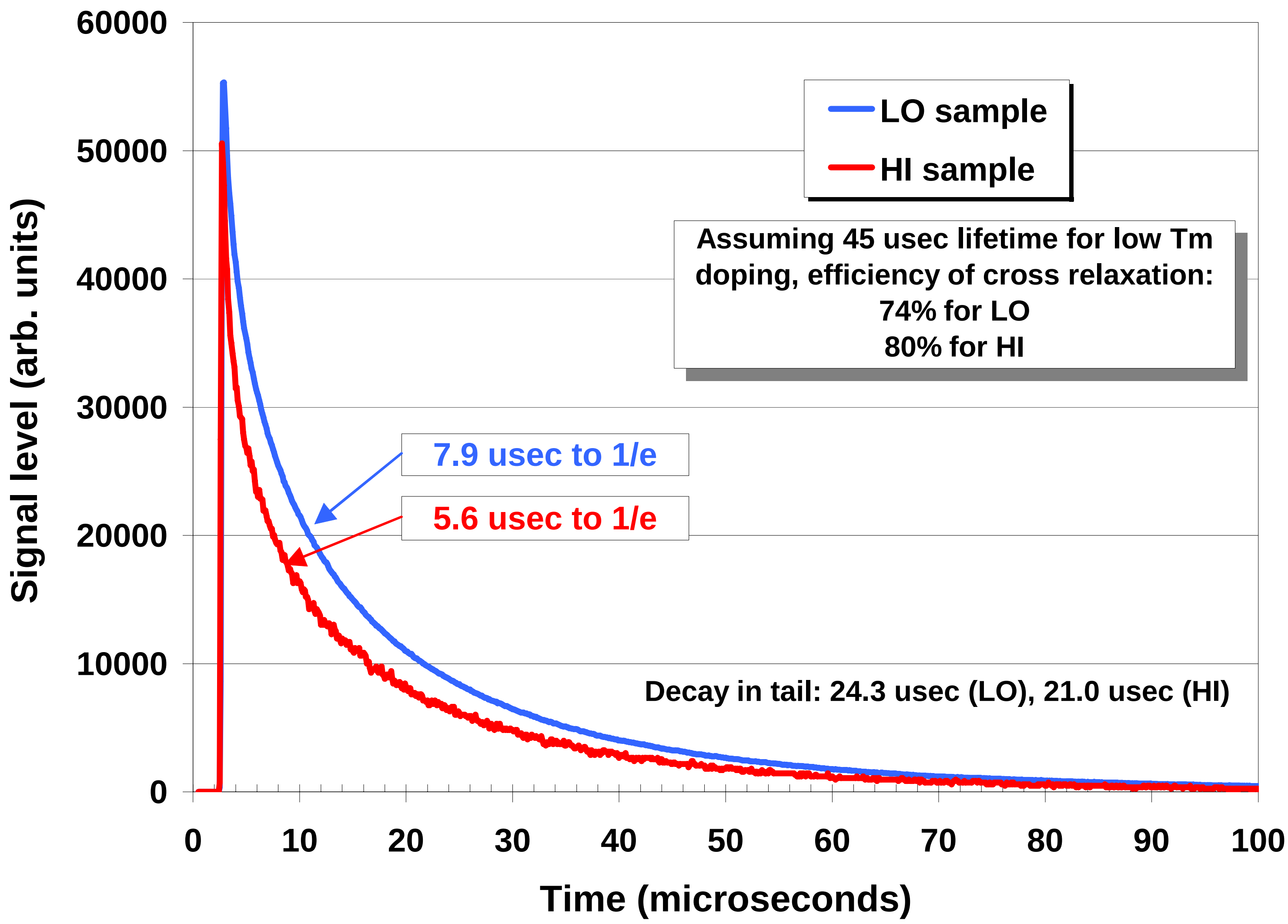


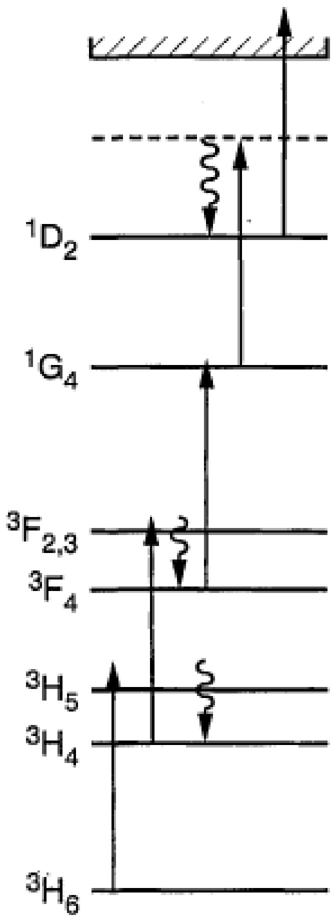
Table 1. Summary of $^3F_4$ decay data from preform samples.

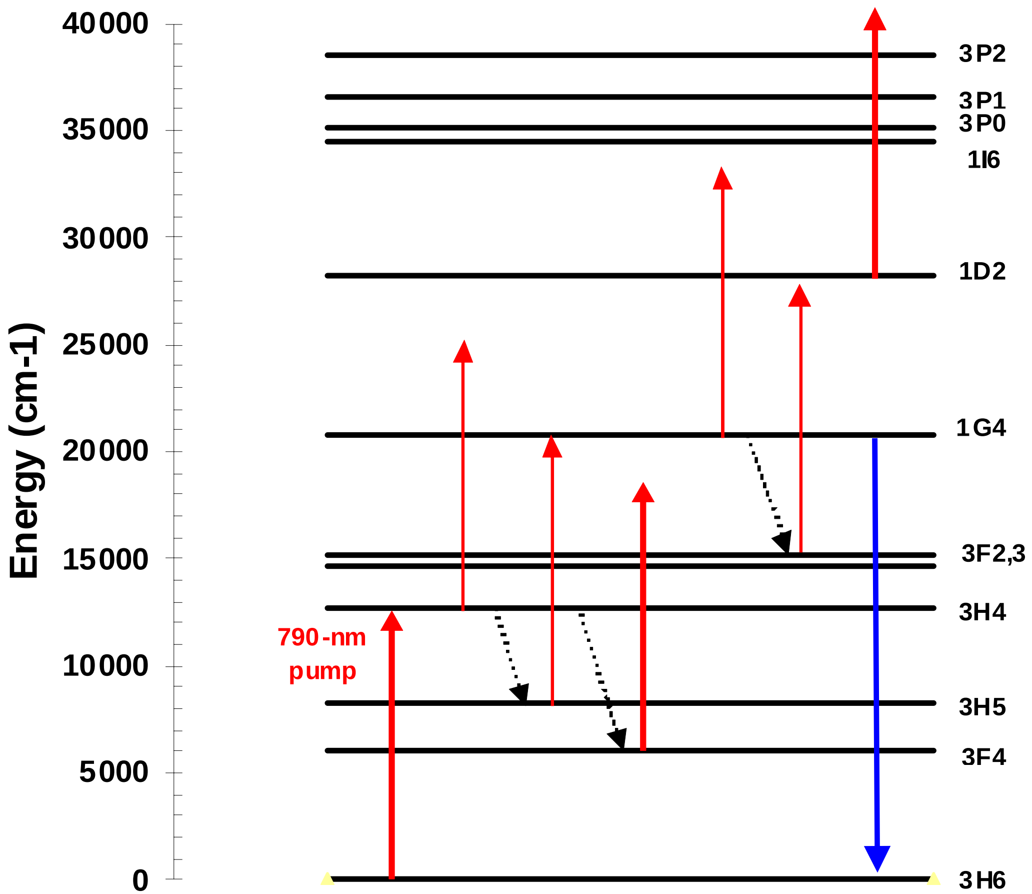
/Sample	1/e (μsec)	τ_1 (μsec)	τ_2 (μsec)	Peak ratio	Area ratio
LO (BB)	504	281	633	0.395	0.176
LO	540	242	635	0.318	0.121
HI	541	273	681	0.402	0.161
LMA-HI1 (BB)	514	197	656	0.329	0.099

800-nm fluorescence provides data on cross-relaxation efficiency



1064-nm pumping created drastic photodarkening 790-nm pumping has not

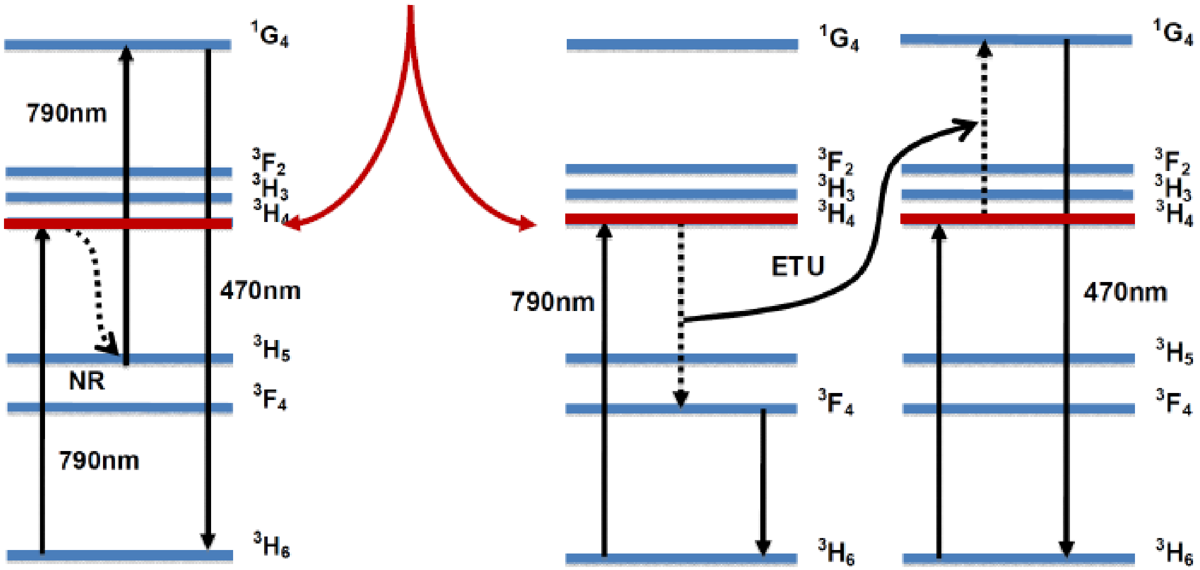




M.M. Broer, D.M. Krol and D.J. DiGiovanni, "Highly nonlinear near-resonant photodarkening in a thulium-doped aluminosilicate glass fiber," Opt. Lett. **18**, 799 (1993).

Population of higher-lying levels with 790-nm pumping

Both process rely upon initial population of the $^3H_4$ level

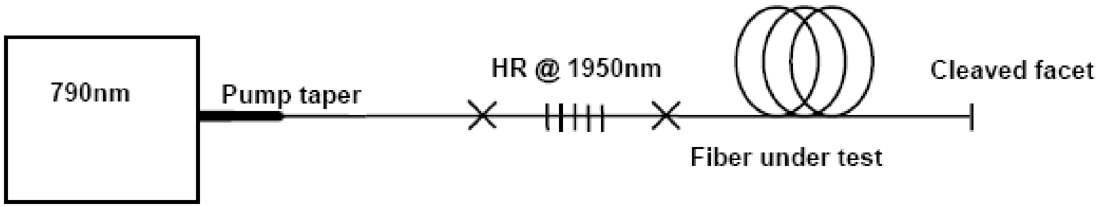


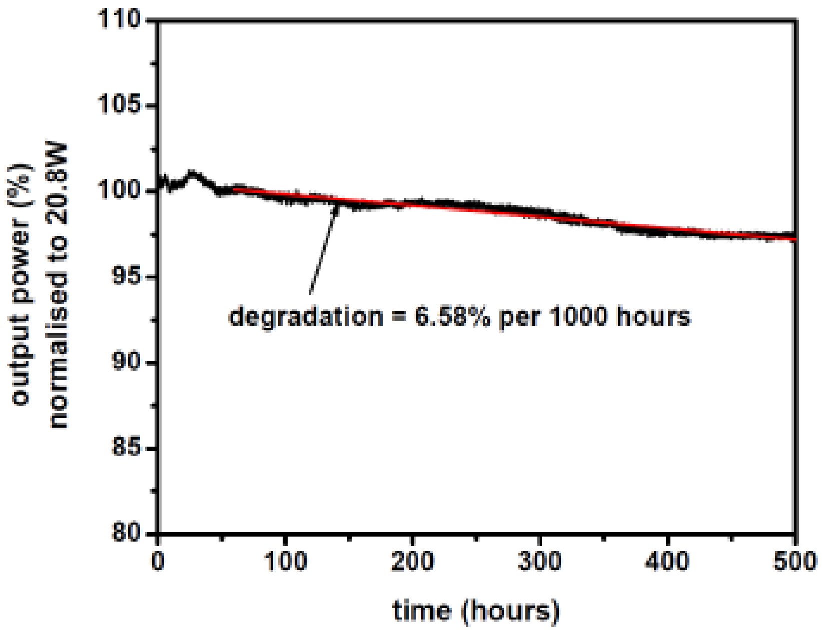
Mitigation of photodegradation in 790-nm-pumped Tm-doped fibers

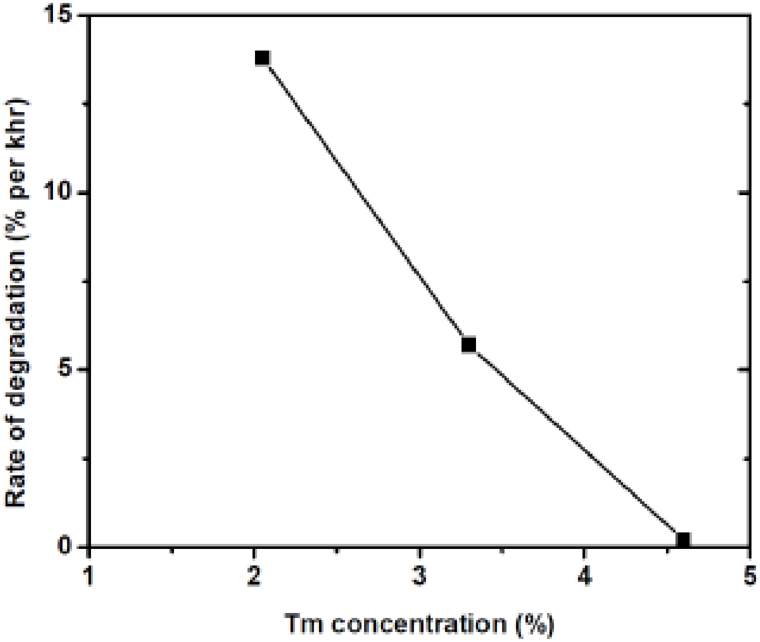
G. P. Frith, Macquarie Univ. A. L. G. Carter, B. N. Samson, J. Faroni, K. Farley, K. Tankala, Nufern G. E. Town, Macquarie Univ.

Paper 7580-09
Photonics West 2010
Courtesy: Gavin Frith

Data shows negligible photodarkening at high [Tm]







Paper 7580-09
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Courtesy: Gavin Frith

Publication

IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 15, NO. 1, JANUARY/FEBRUARY 2009

Tm-Doped Fiber Lasers: Fundamentals and Power Scaling

Peter F. Moulton, *Senior Member, IEEE*, Glen A. Rines, *Member, IEEE*, Evgueni V. Slobodtchikov, Kevin F. Wall, Gavin Frith, Bryce Samson, and Adrian L. G. Carter

***Abstract*—We describe fundamental measurements of the properties of thulium (Tm)-doped silica and power scaling studies of fiber lasers based on the material. Data on the high-lying Tm:silica energy levels, the first taken to our knowledge, indicate that pumping at 790 nm is unlikely to lead to fiber darkening via multiphoton excitation. Measurement of the cross-relaxation dynamics produces an estimate that, at the doping levels used, as much as 80% of the decay of the Tm level pumped is due to cross relaxation. Using a fiber having a 25-μm-diameter, 0.08 numerical aperture (NA) core, we observed fiber laser efficiencies as high as 64.5% and output powers of 300 W (around 2040 nm) for 500 W of launched pump power, with a nearly diffraction-limited beam. At these efficiencies, the cross-relaxation process was producing 1.8 laser photons per pump photon. We generated 885 W from a multimode laser using a 35-μm, 0.2-NA core fiber and set a new record for Tm-doped fiber laser continuous-wave power.**

***Index Terms*—Fiber lasers, spectroscopy, thulium (Tm) doping.**

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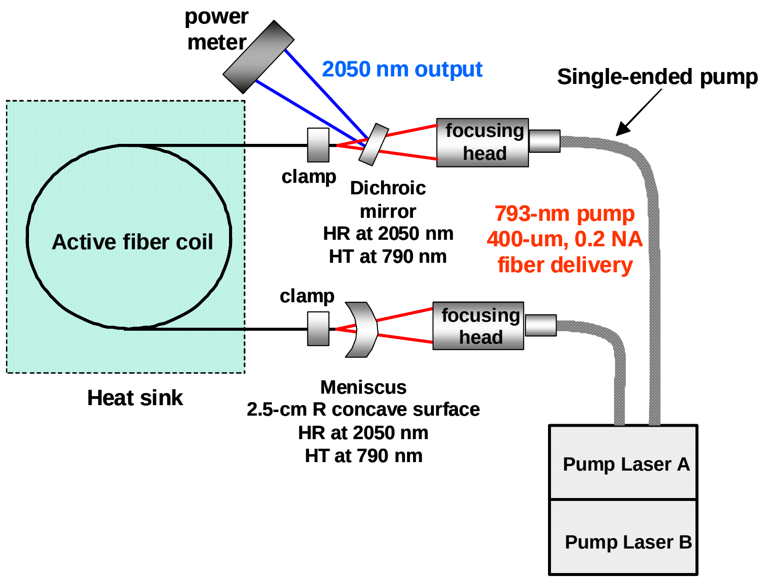
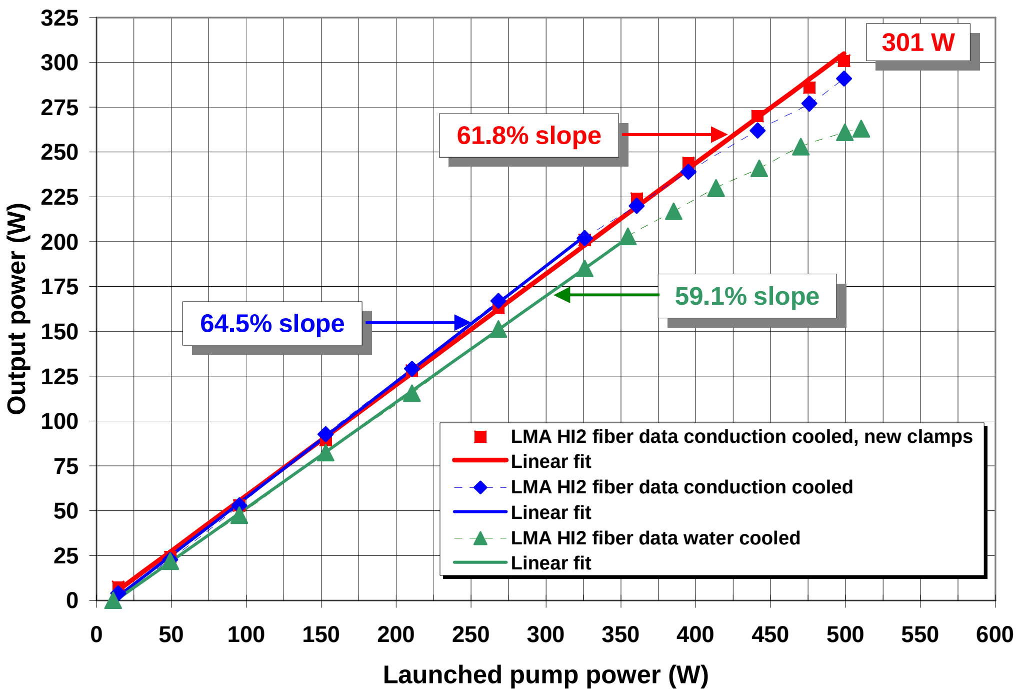
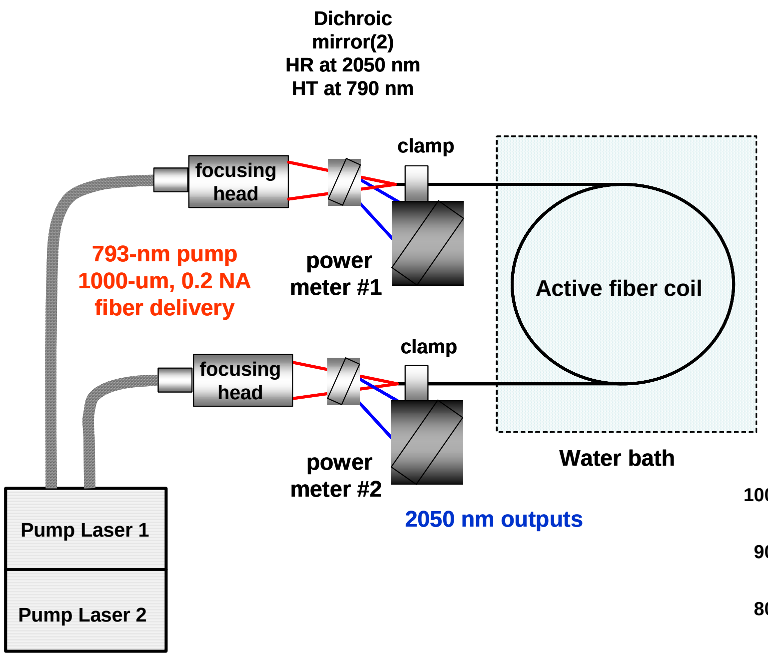
Early Q-Peak results scaling to 300 W, single-mode

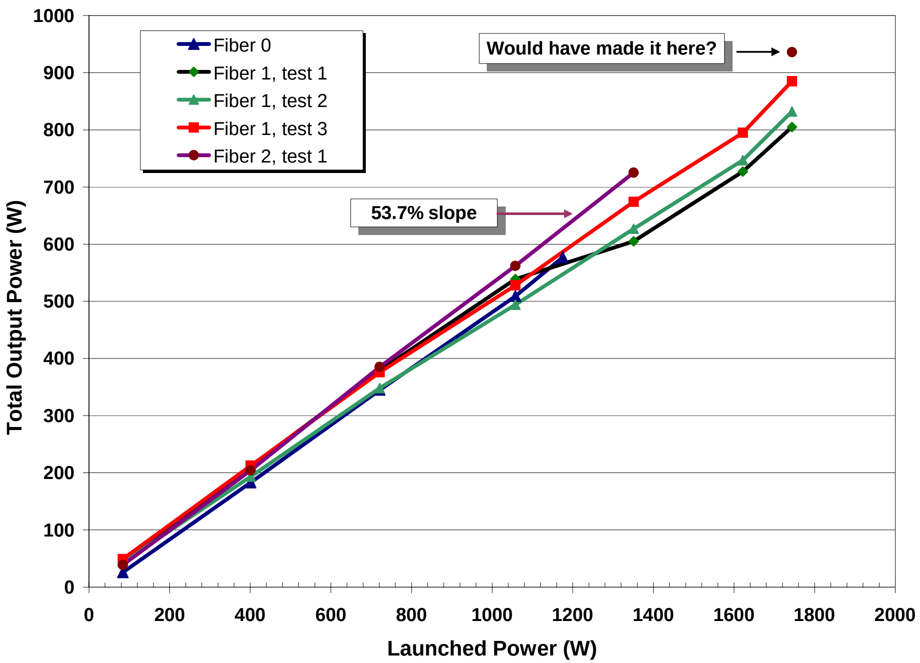


Gain fiber: 5-m long, 3-m undoped ends (2)
Core: 25 μm in diameter, NA: 0.08.
Pump cladding: 400-μm in diameter

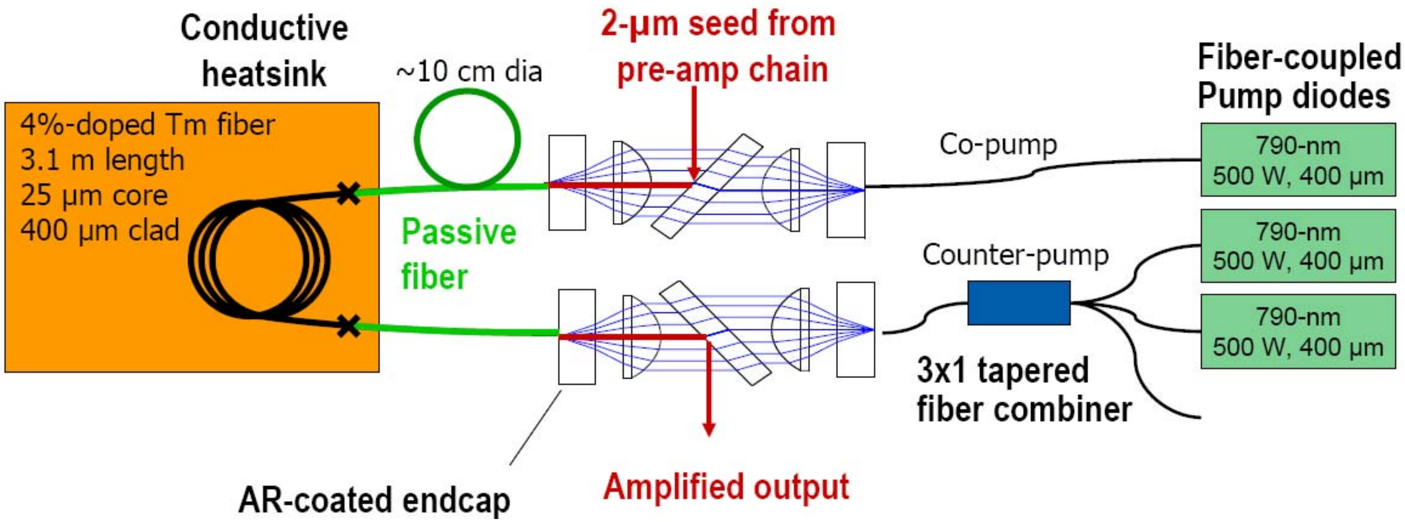


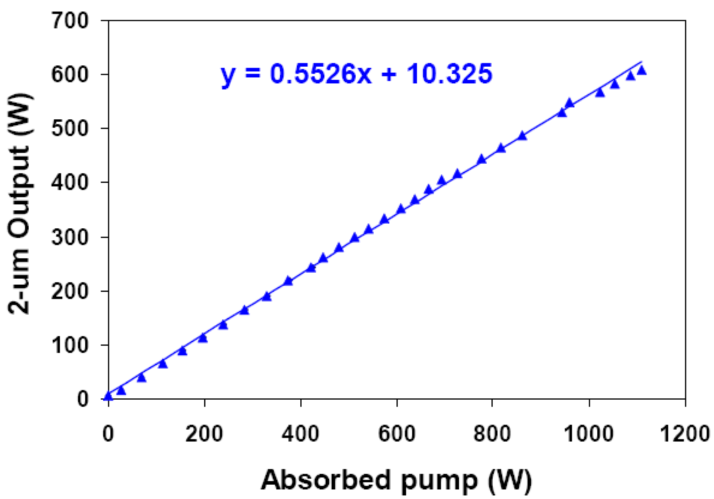
Higher powers (885 W) with bigger pumps and spectacular damage

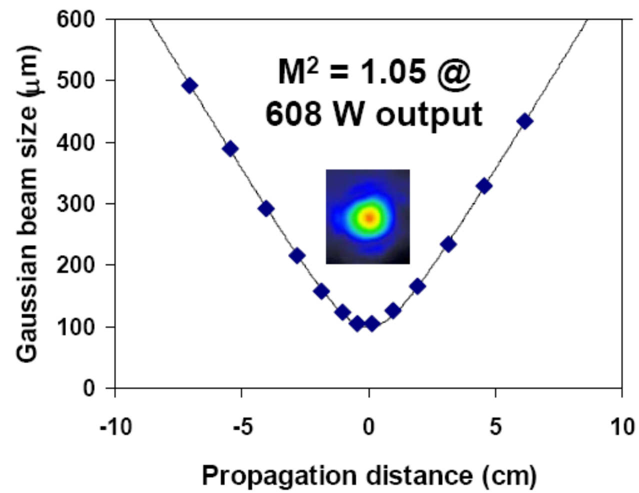




NGAS 600-W Single-frequency MOPA (PW 2009)



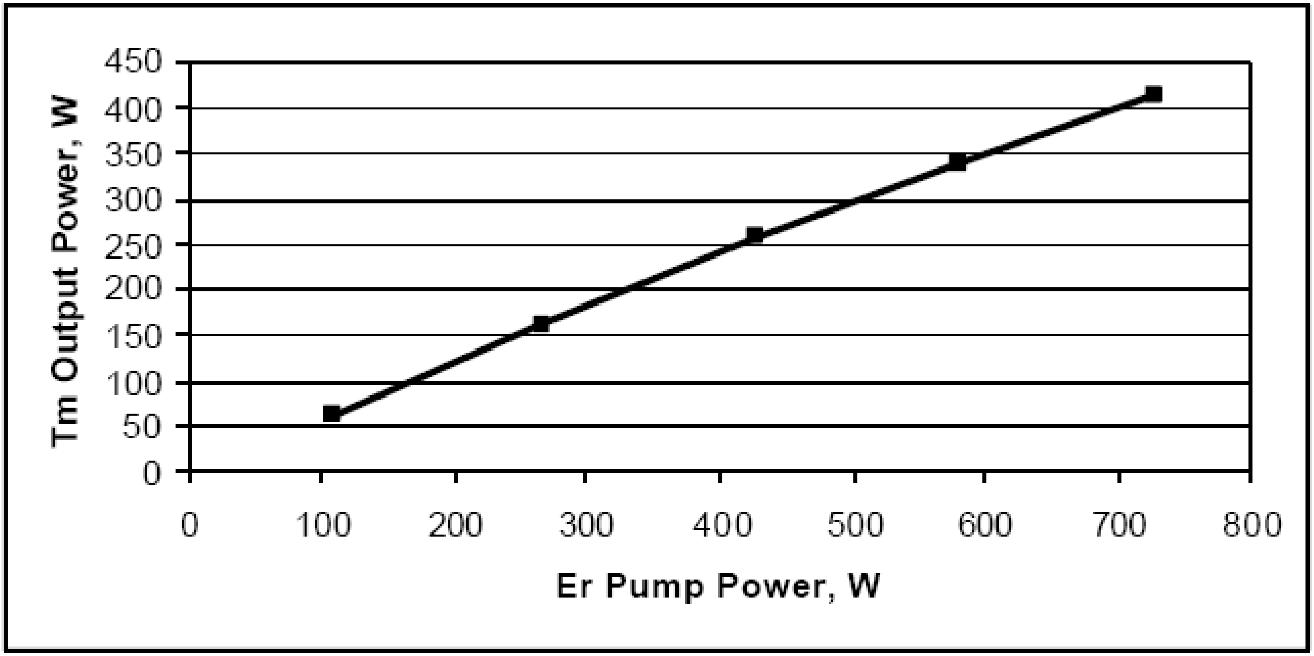




Gregory D. Goodno, Lewis D. Book, and Joshua E. Rothenberg

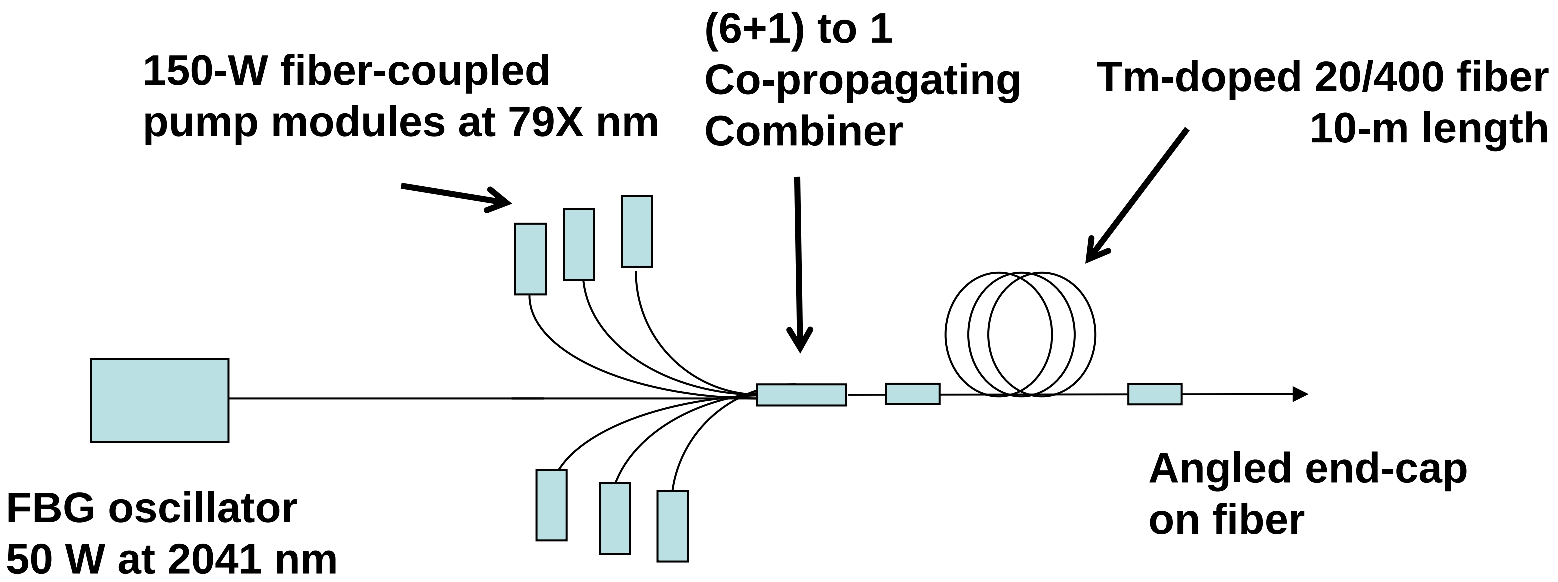
IPG 415-W all-glass result (CLEO Europe 2007)

The laser setup was consist of an 8 meters of low concentration Tm-doped fiber with core diameter of ~20 mm and a pair of fiber Bragg gratings (FBG), fusion spliced with an active fiber, forming a laser cavity. The output of the Tm fiber laser was terminated by a single-mode fiber with mode field diameter (MFD) of LP01 mode and wavelength of the cutoff of LP11 equal to 14 mm and 1450 nm respectively. The reflectivity of output FBG was ~1dB. The double clad Tm fiber was end-pumped to the cladding through the strong FBG by pump fiber assembly consisting of 18 40W CW Er fiber lasers at 1567nm. The total in-fiber power of this pump assembly output more than 720W CW. The 1567nm pumping of Tm fibers compare to 793nm pumping advantage in no up-conversion processes that leads to fiber degradation due to photodarkening.

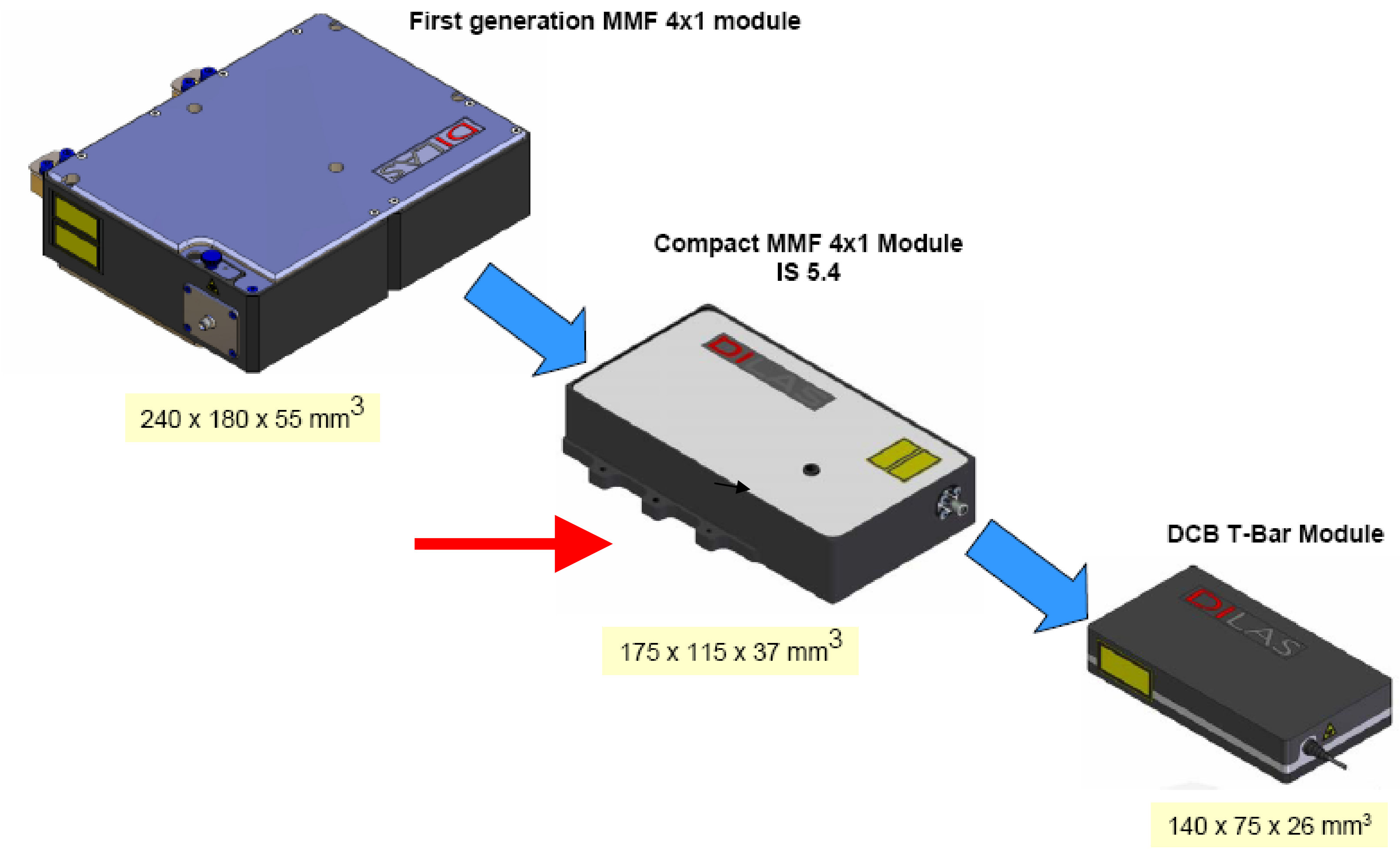


M. Meleshkevich, N. Platonov, D. Gapontsev, A. Drozhzhin, V.Sergeev, V.Gapontsev

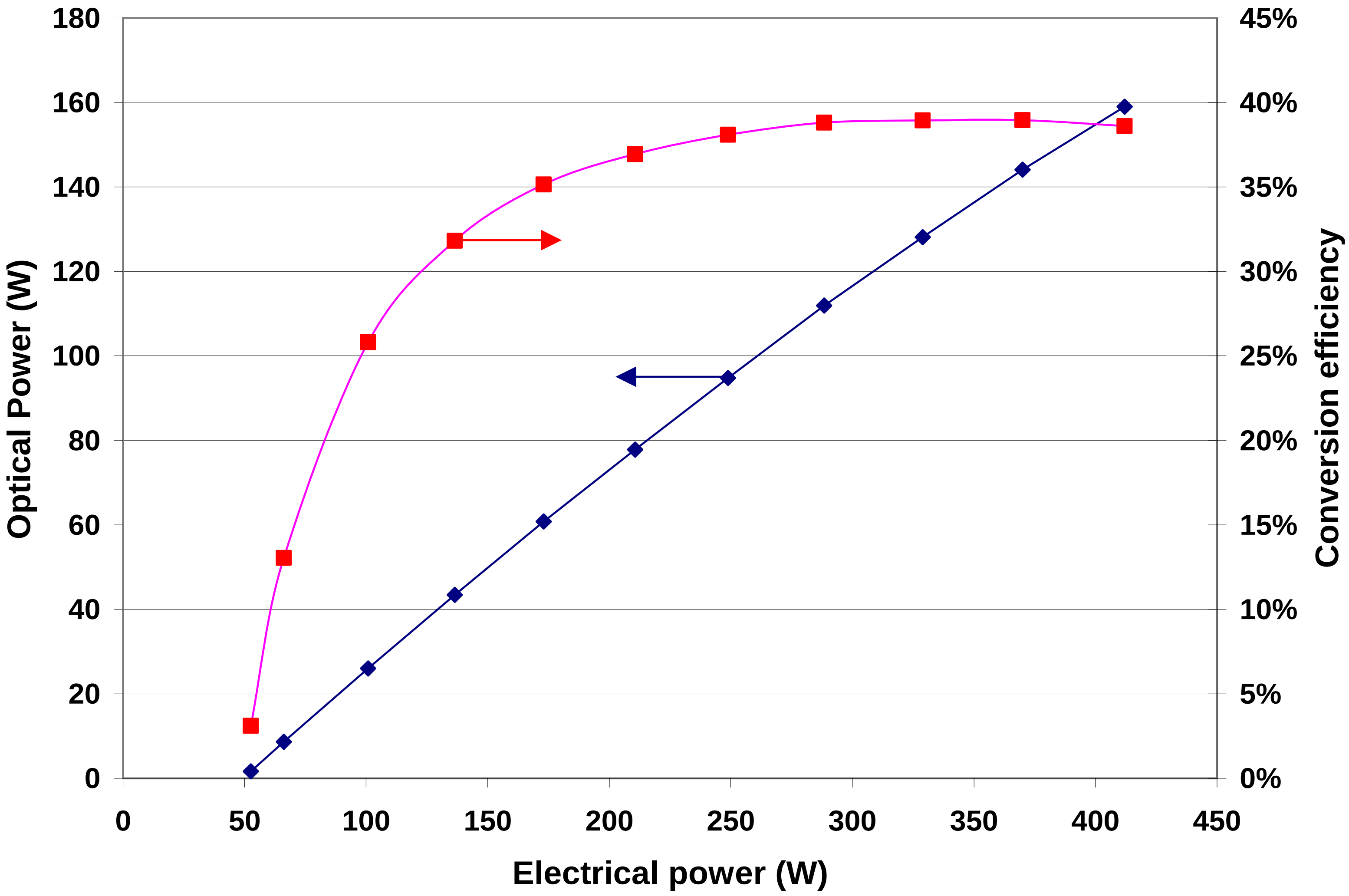
Components for all-glass laser – single stage



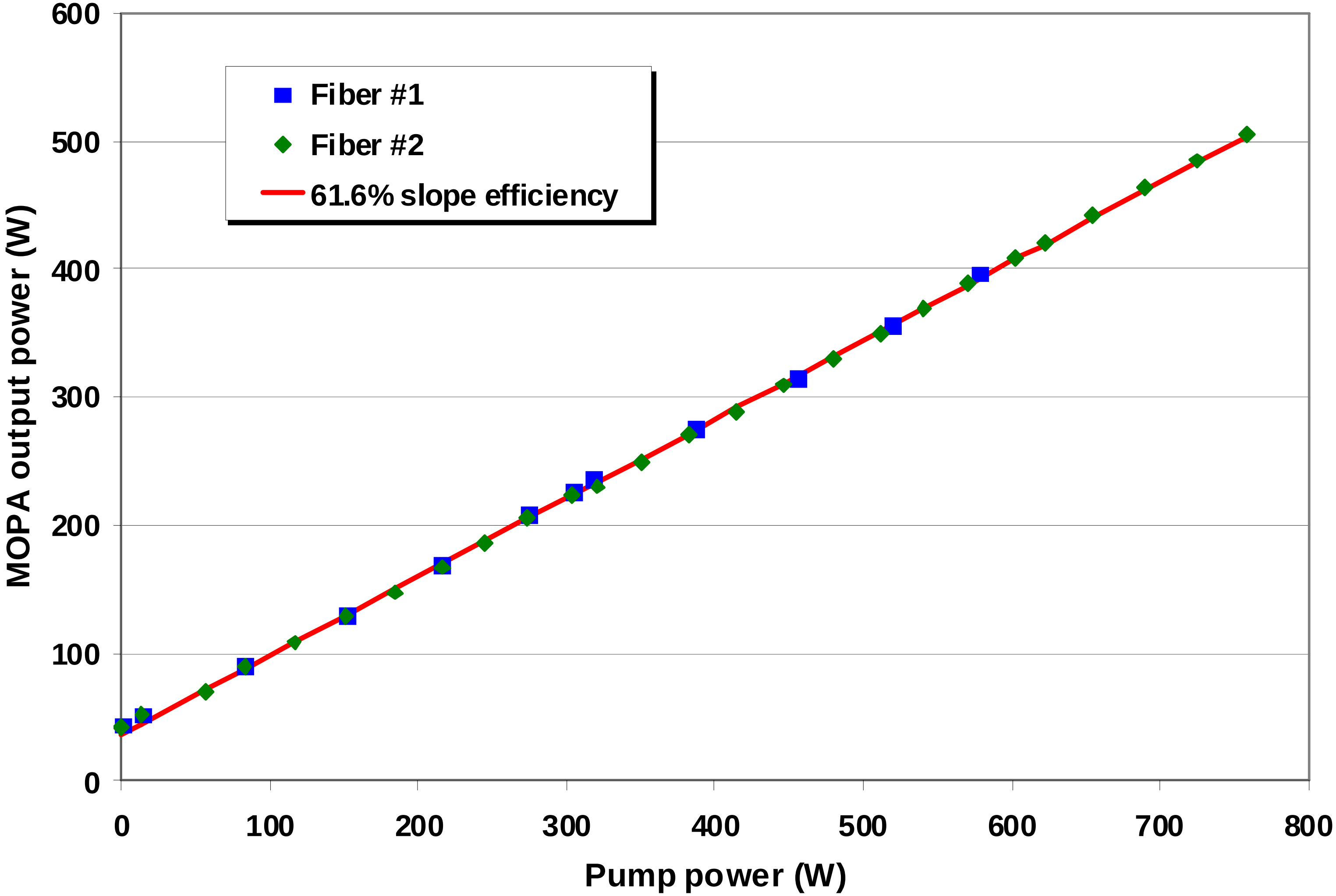
Using DILAS "second generation" fiber-coupled diodes



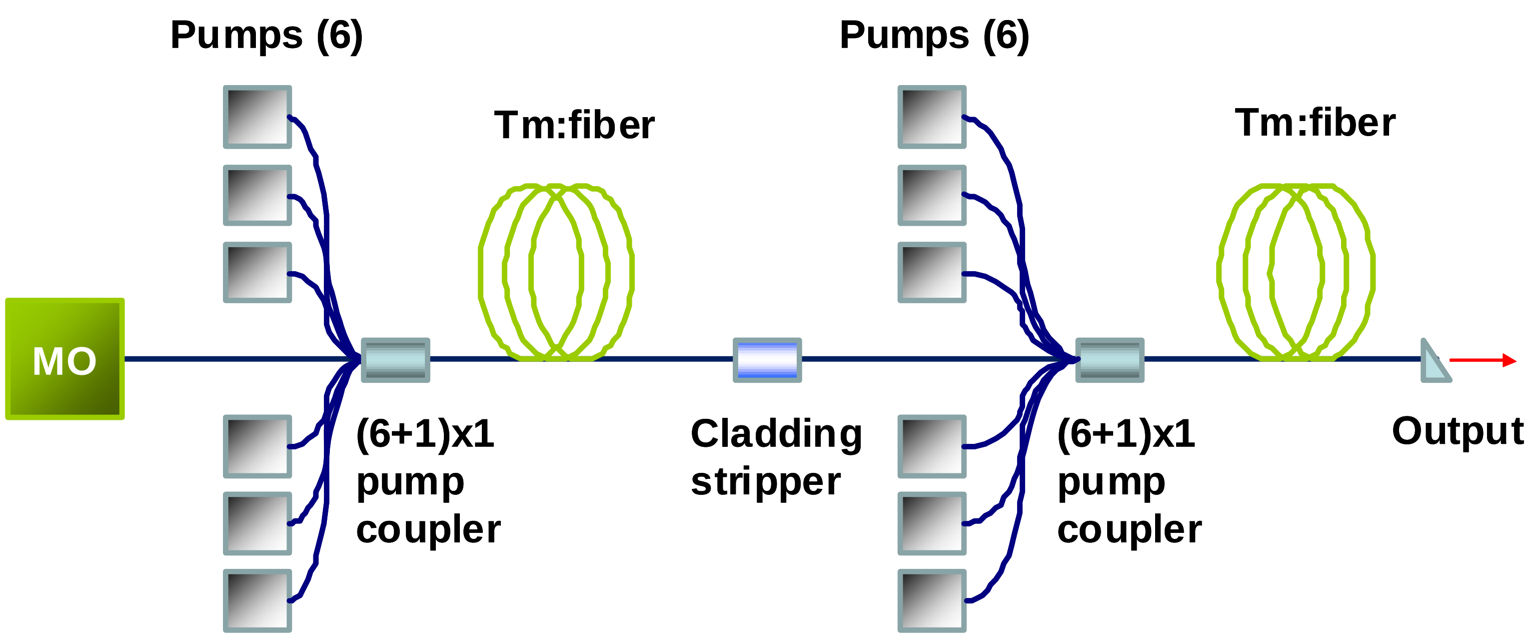
DILAS modules have nearly 40% electrical-optical conversion



Results from single stage: >500 W



Two-stage power amplifier



MO

50 Watts at 2045-nm

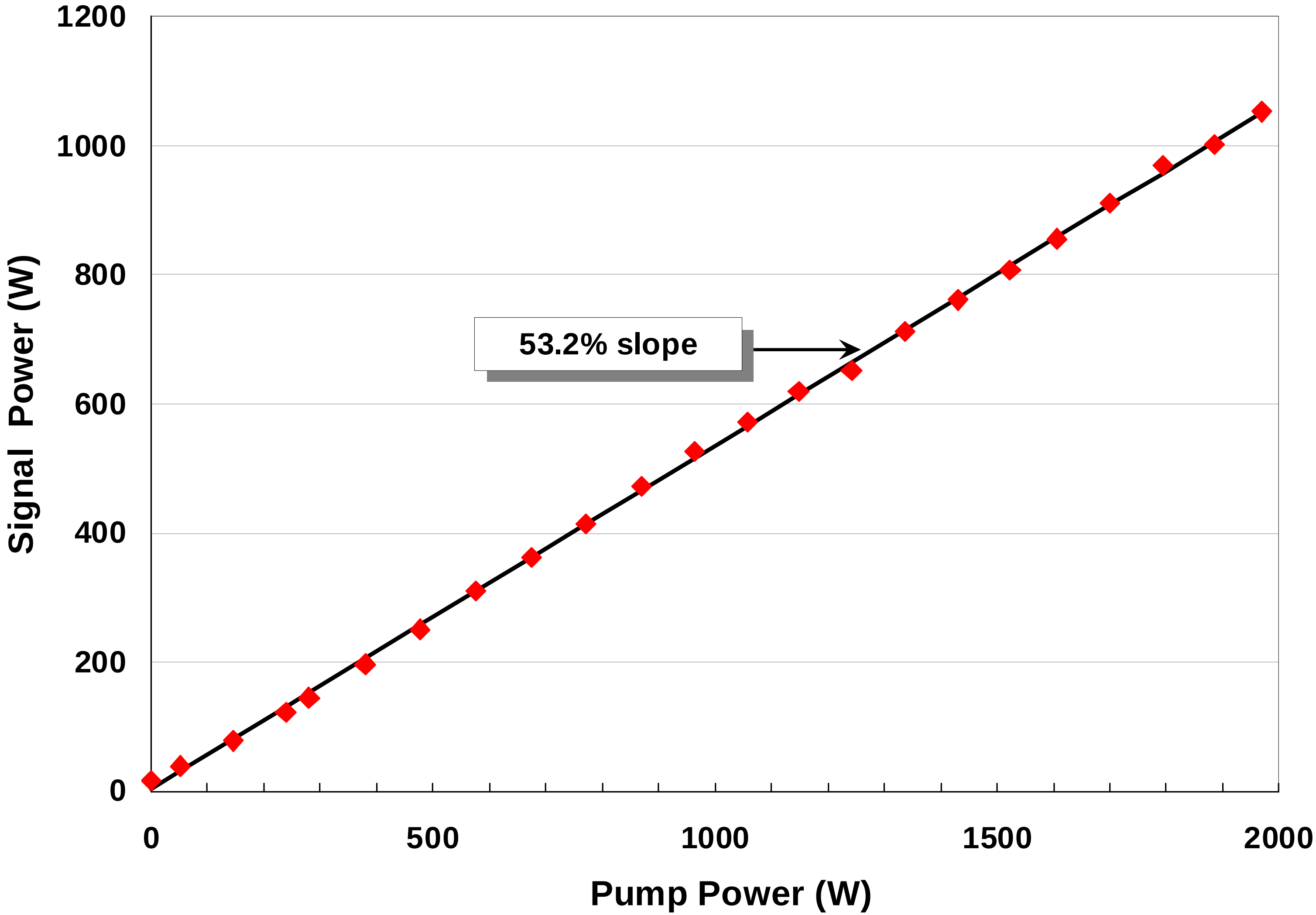
1st Stage

12m LMA-TDF-20/400 active fiber

2nd Stage

12m LMA-TDF-20/400 active fiber

> 1 kW of power output at 2045 nm



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Co-doping with Al reduces Tm clustering, allows increased efficiency at higher Tm concentrations

Table 1. Measured Specifications and Manufacturers of the Fibers Used in the Experiments

Fiber Number	Al^{3+}:Tm^{3+} Ratio	Area Ratio	α_{eff} (m^{-1})	α_{core} (m^{-1})	N_0 (wt. %)	Manufacturer
1	5:1	0.0063	0.16	26	0.7	Nufern
2	2:1	0.0074	0.34	48	1.2	Nufern
3	9:1	0.0032	0.16	50	1.3	OFTC[a]
4	10:1	0.0039	0.22	58	1.6	OFTC[a]

[a]Optical Fibre and Technology Centre, University of Sydney.

S.D. Jackson and S. Mossman, Appl. Opt. 42, 2702 (2003).

Slope efficiencies:

Fiber 1: 21%

Fiber 2: 8%

Fiber 3: 41%

Fiber 4: 46%

But, doping the core with Al increases the index and the core NA

Nonlinear effects: wavelength scaling issues for fiber lasers

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

V < 2.405 for single-mode fiber

a is core radius, λ is wavelength

Core area for constant V: **scales as λ^2**

Optical damage fluence: **scales as λ**

Raman gain: **scales as 1/ λ**

Brillouin gain (theory): **constant in λ**

(smaller linewidth (1/ λ^2) cancels smaller gain)

Brillouin gain (actual): **reduces with λ**

(more sensitive to inhomogeneous effects)

Nonlinear effects: Tm-doped fibers compared to Yb-doped fibers

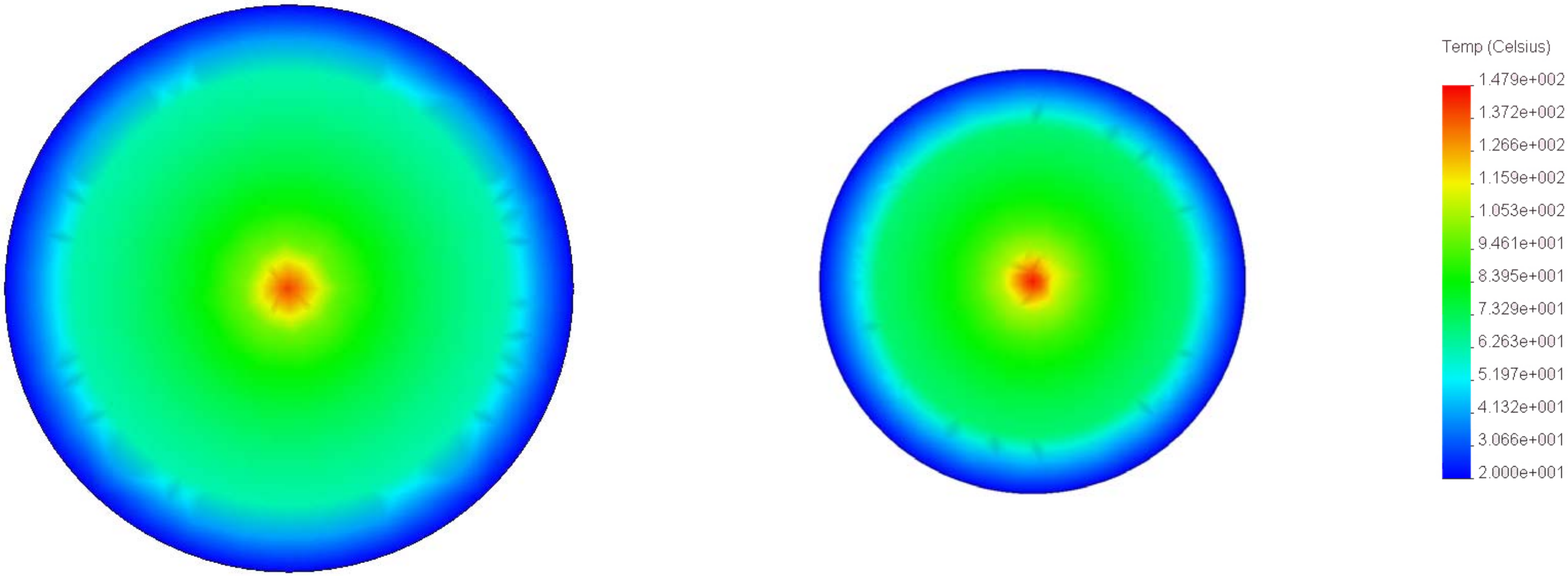
- For the same V parameter, compared to Yb-doped fibers, Tm-doped fibers can have:
  - 8X higher fiber core damage threshold
  - 8X higher stimulated Raman scattering threshold
  - At least 4X higher stimulated Brillouin threshold

- The challenge for fiber makers is to scale up the core diameter for Tm-doped fibers and keep single-mode operation

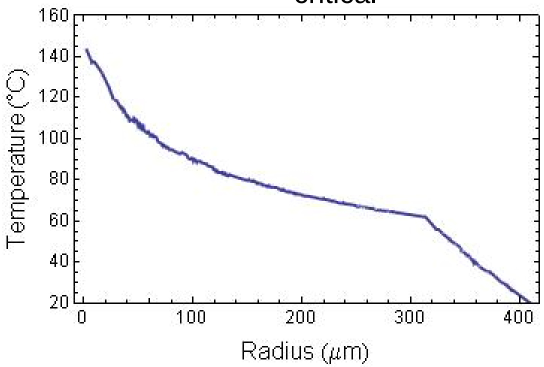
- IPG 10-kW single-mode laser reportedly has about a 30-μm core diameter and is near Raman limit

- With a 60-μm core, a cw Tm:fiber can operate at 80 kW (!?)

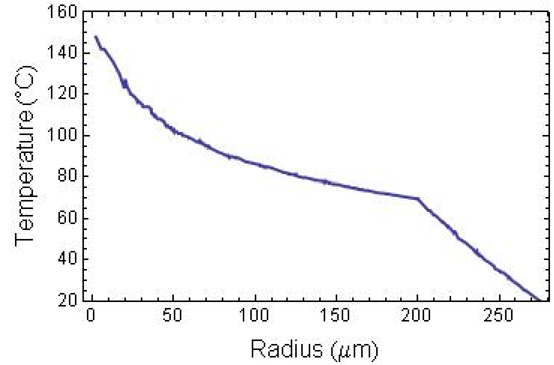
Thermal modeling for 200 W/m indicates cladding/buffer temperature well below 100 C



35/625/819 $P_{critical}$ = 382 W/m



25/400/550 $P_{critical}$ = 323 W/m



The cladding/ buffer interface reaches 100 C sooner for the smaller diameter fiber even with a thinner buffer

Power limits from heat and pumping

- Thermal limits to power output - assume
  - 300 W/m maximum thermal load
  - Laser slope efficiency (wrt absorbed power) of 70%
  - 10 m of fiber, 90% absorption
- Can pump with 8.6 kW of power into fiber (pumping from both ends) at maximum thermal load, leading to > 5 kW of output
- Present diode technology (200 μm, 0.22 NA fiber) provides 150 W, with 12 input ports, 1.8 kW of pump power is possible
- Future diode technology (WBC, Teradiode, >1 kW in 200 μm, 0.22 NA) may finally allow the thermal limit to be reached
- Scaling to higher power with conventional diode pumps requires either series connection of fiber amplifiers (nonlinearities will limit) or beam combination (complexity)
- Limits to power now are, in fact, due to the limited brightness of diode-laser pumps
- In the future, limits will transition to thermal

Summary

- Tm:fiber lasers provide high powers at “eyesafe(r)” wavelengths
- Spectroscopic understanding of Tm:silica has been improved, with photodarkening possibility still requiring more investigation
- High-power, “all-glass” operation of a 79X-nm pumped Tm:fiber laser has been made possible by development of:
  - High-brightness, fiber-coupled pump lasers
  - Fiber-based, (6+1):1 pump-coupling optics
- To date, power levels achieved are:
  - > 500 W with six pump lasers
  - > 1 kW with twelve pump lasers
- Based on the fibers used, the results represent single-mode operation at 2045 nm and the highest cw power level (to our knowledge) ever generated in this wavelength range
- Improvements are possible in all of the components, leading to higher powers and efficiencies
- Substantial further scaling of this approach will rely on development of higher-brightness pump lasers
- Fundamental (nonlinear effects) cw power limits are well above 10 kW