Survey Report: Laser R&D

Peter Moulton

VP/CTO, Q-Peak, Inc.

DLA-2011

ICFA Mini-Workshop on Dielectric Laser Accelerators

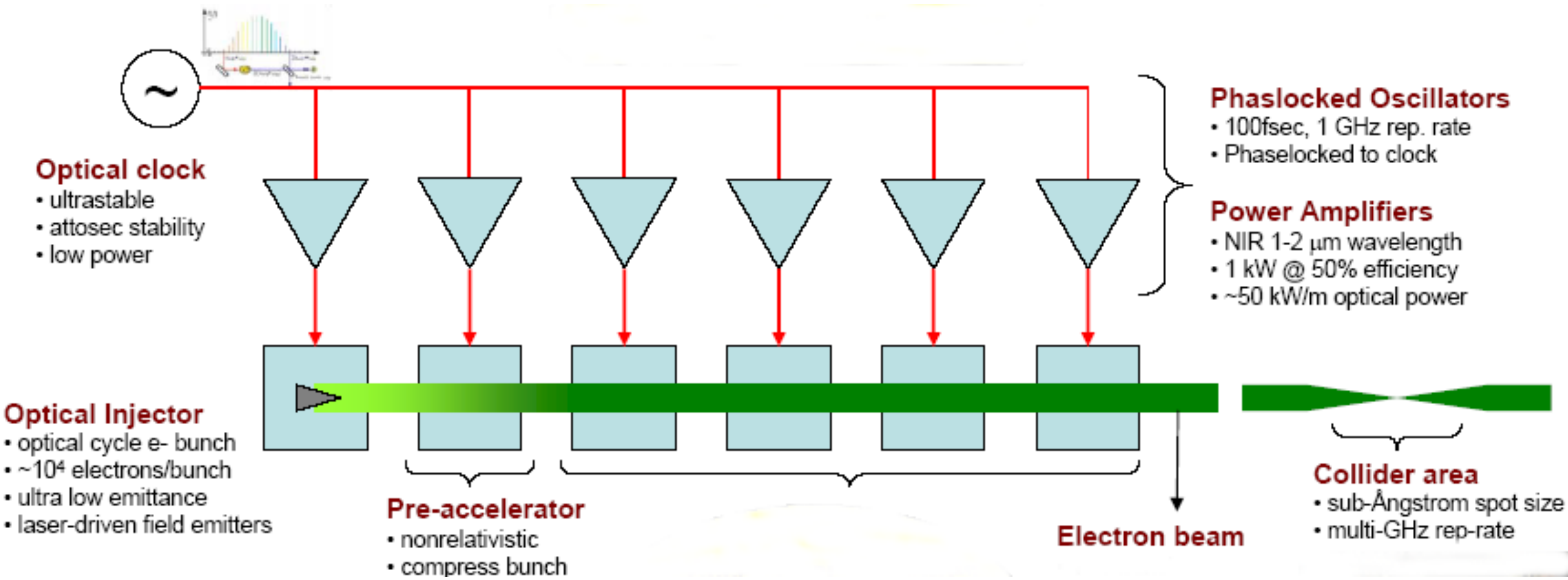
September 15, 2011

SLAC, Menlo Park, CA

Outline

- DLA laser requirements (one version)
- Quick review of suitable laser technology
- Tm:fiber lasers for DLAs
  - Current technology
  - Prospects

One possible accelerator design needs efficient, high-power lasers



The low-power laser components (optical clock, phase-locked oscillators) in the system can be engineered based on existing solid state laser technology

The power amplifiers remain a challenge.
The pulsewidth and wavelength range requires a solid state laser.
The solid state solution is based on fiber-laser technology.

Highly stable optical clocks are old news

Carrier-Envelope Offset Phase-Locking With Attosecond Timing Jitter

Florian W. Helbing, Günter Steinmeyer, *Member, IEEE*, and Ursula Keller, *Senior Member, IEEE*

Abstract**—Inside a femtosecond laser oscillator, no coupling mechanism between the propagation speeds of the carrier and the pulse envelope exists. Therefore, the relative delay between carrier and envelope of a femtosecond oscillator will exhibit irregular fluctuations unless this jitter is actively suppressed. Both intensity and beam pointing fluctuations in the laser can introduce carrier-envelope phase changes. Based on our analysis, we are capable of reducing or avoiding certain mechanisms by proper design of the laser cavity. We use such an optimized cavity to stabilize the carrier envelope-phase to an external reference oscillator with a long-term residual jitter corresponding to only 10 attoseconds in a (100 kHz–0.01 Hz) bandwidth. This is the smallest long-term timing jitter of a femtosecond laser oscillator demonstrated to date. However, it is important to note that this stabilization was obtained with an f-to-$2f$ heterodyne technique using additional external spectral broadening in a microstructure fiber which introduces additional carrier-envelope phase noise. We present a direct heterodyne measurement of this additional carrier-envelope phase noise due to the continuum generation process.**

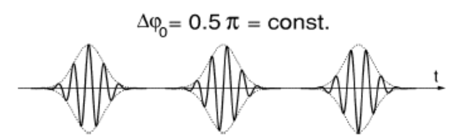


Fig. 3. Electric field $E(t)$ of three subsequent pulses from a mode-locked laser, i.e., the time-domain picture of the comb in Fig. 4. Envelope $\pm A(t)$ is shown as dashed lines. Here, the electric-field patterns of the pulses experience a *constant* pulse-to-pulse phase *shift* $\Delta\varphi_0 = 0.5\pi$ while the value of φ_0 increases with time.

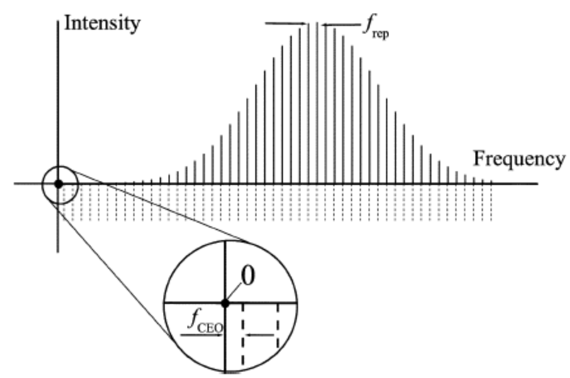


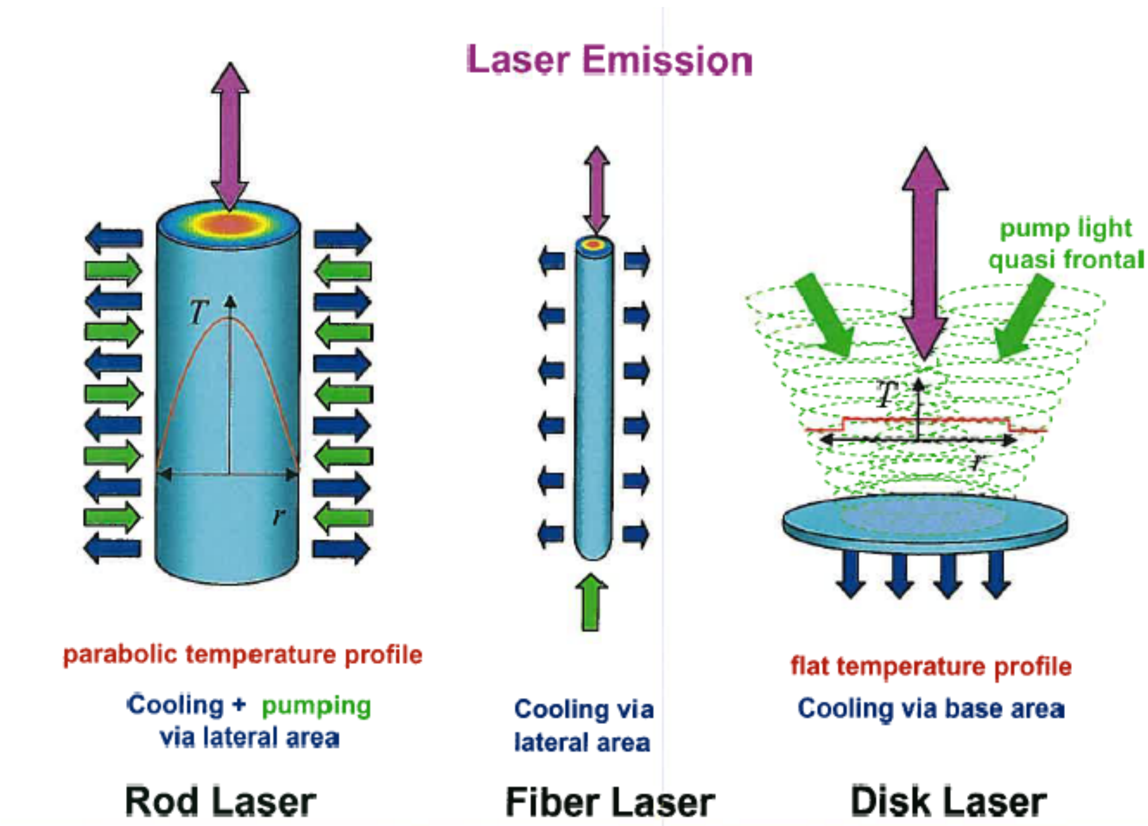
Fig. 4. Equidistant frequency comb of a mode-locked laser. Comb lines are spaced by the repetition rate f_{rep} and exhibit a nonvanishing offset frequency f_{CEO} at zero frequency unless the electric field pattern exactly reproduces from pulse to pulse (compare to Fig. 3). Note the difference to the case of a vanishing CEO frequency as depicted in Fig. 2.

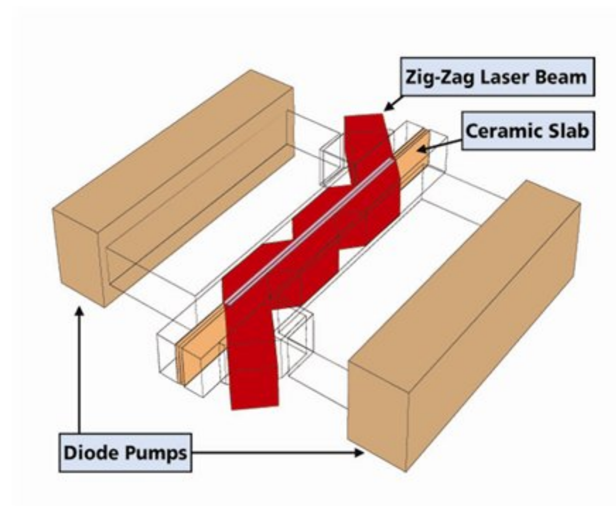
Hansch and Hall win Nobel Prize for Optical Combs

Stockholm
December 10, 2005

Variety of formats for high-beam-quality, high-power solid state lasers

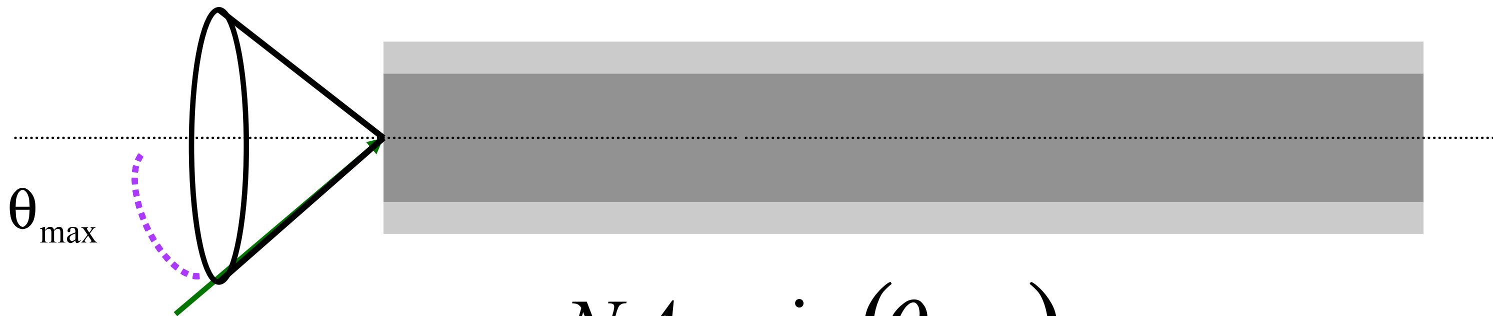
How to get optical pump power in and laser and heat power out?



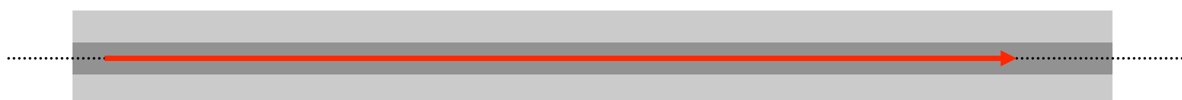


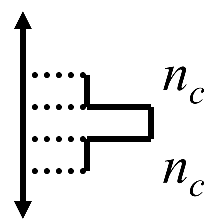
Slab (zig-zag) Laser

Step index fiber - single mode design



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





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

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

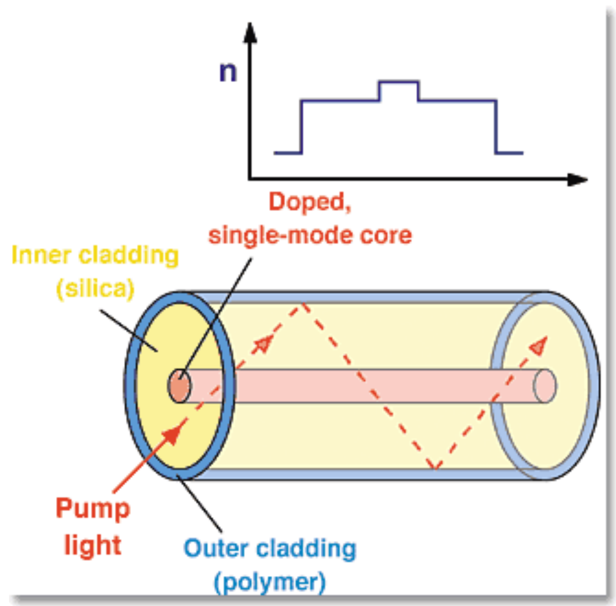
a is core radius, l is wavelength

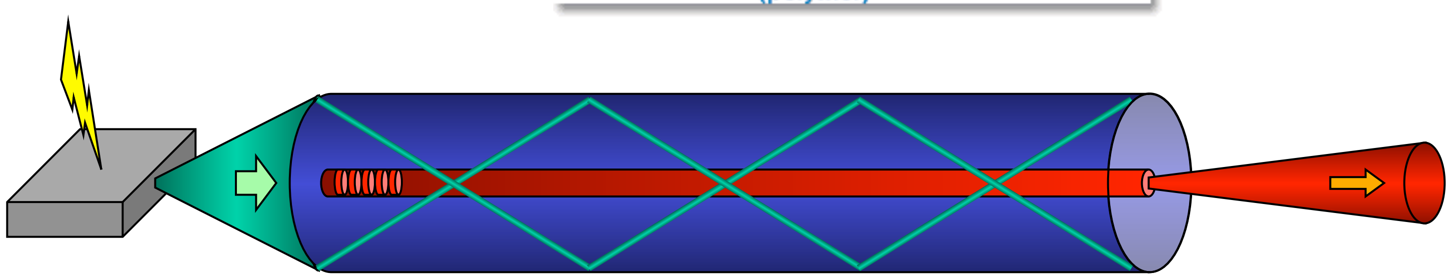
V < 2.405 for single-mode fiber

In general, base fiber material is SiO_2 (fused silica)

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

Traditional single-mode fiber lasers need single-mode pumps but...



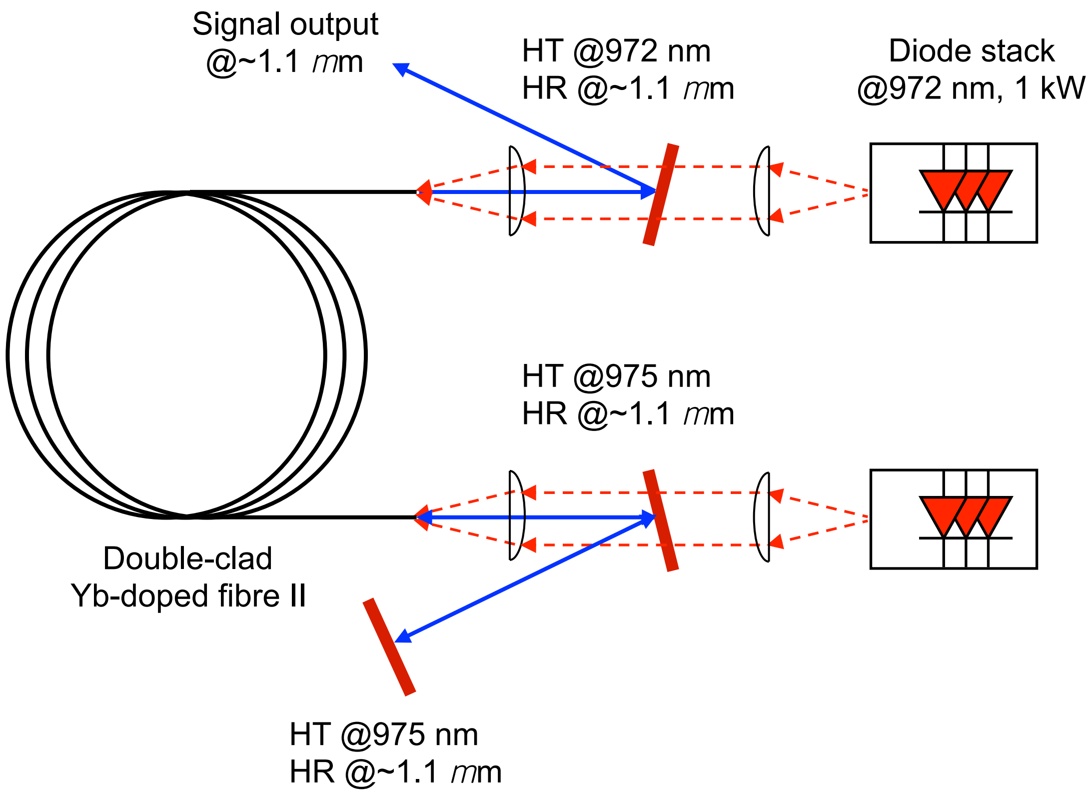


Elias Snitzer first described cladding pumped lasers in 1988

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

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

High-power double-clad fiber lasers facilitated by advances in diode-lasers



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

SORC results: 1.4 kW single-fiber laser

$M^2 = 1.4$

Core: 40 um, NA <0.05
Cladding: (D-shaped) 650/600 um
NA 0.48
Fiber length: 12 M

Thanks to Mike O'Connor at IPG for these slide

Recent Progress in Scaling High Power Fiber Lasers at IPG Photonics

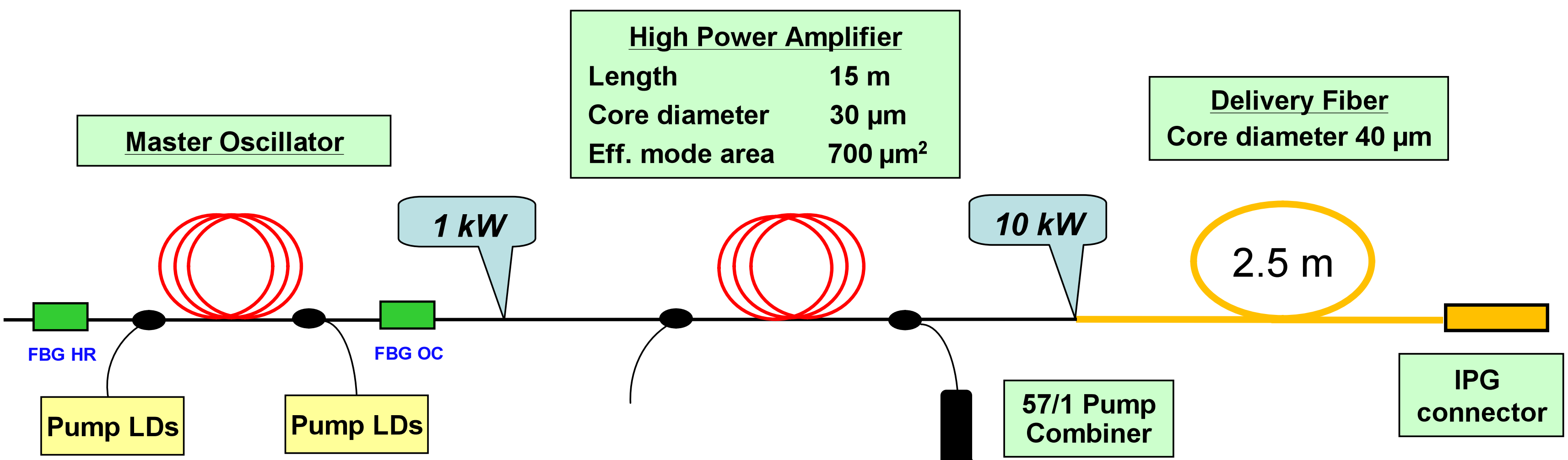
IPG PHOTONICS®

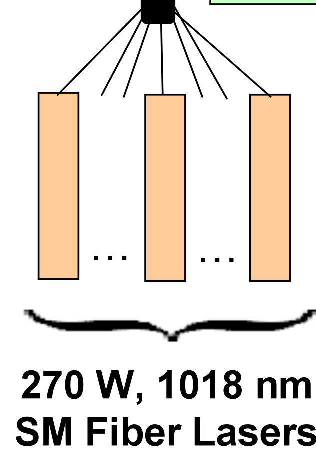
22nd Annual Solid State and Diode Laser Technology Review

Dr. V. Gapontsev, V. Fomin, A. Yusim

Newton, Massachusetts, July`09

YLS-10000-SM Optical Schematic

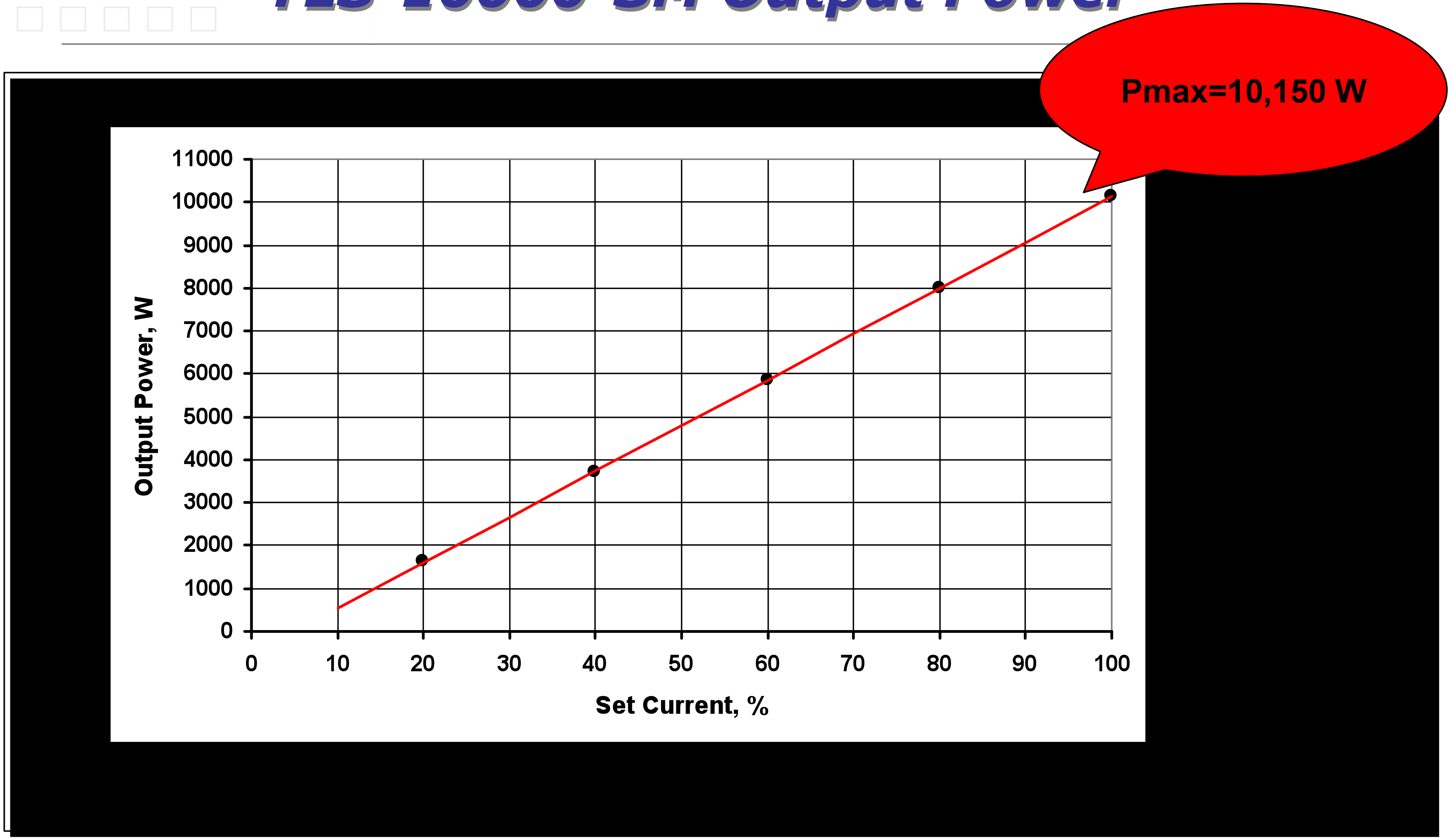




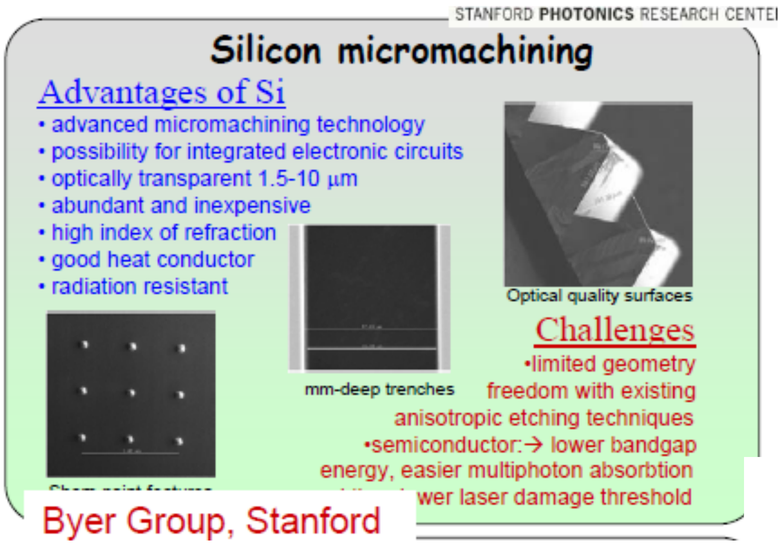
YLS-5000-SM	YLS-10000-SM
Pump lasers quantity	
24	***47***
Effective mode area	
500 µm²	***700 µm²***
Delivery fiber length	
5 m	**2.5 m**

IPG PHOTONICS

YLS-10000-SM Output Power



Materials at long wavelengths may have higher damage thresholds (Si especially)

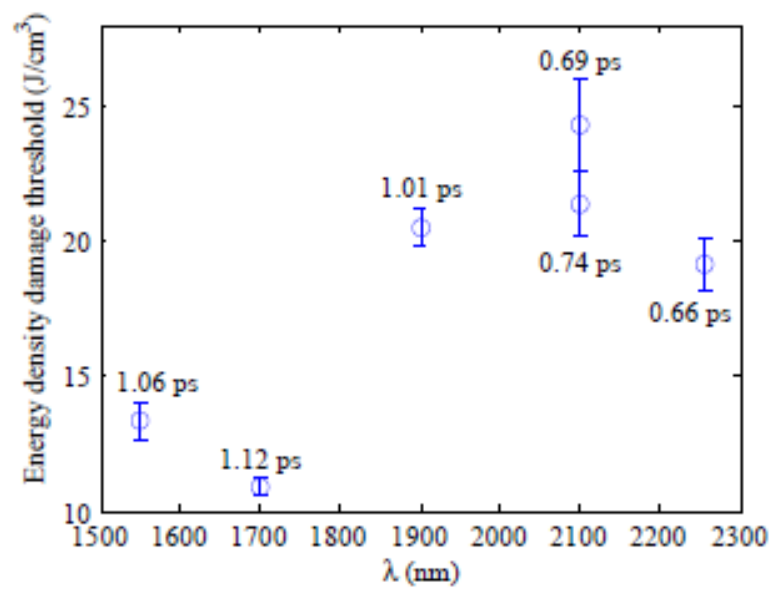


E163: Laser Acceleration of Electrons at the NLCTA

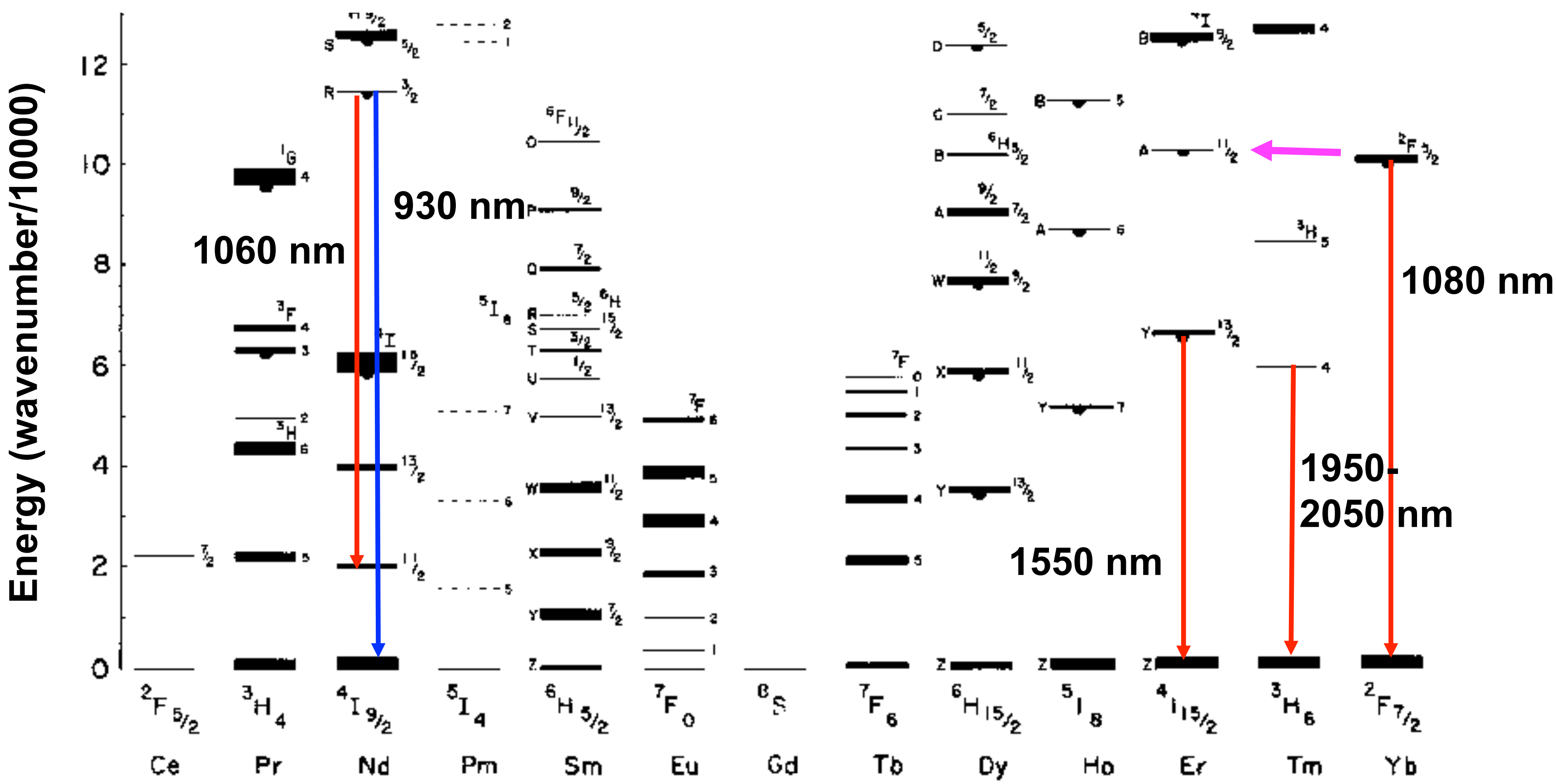
E. R. Colby

Photonic Crystal Laser-Driven Accelerator Structures

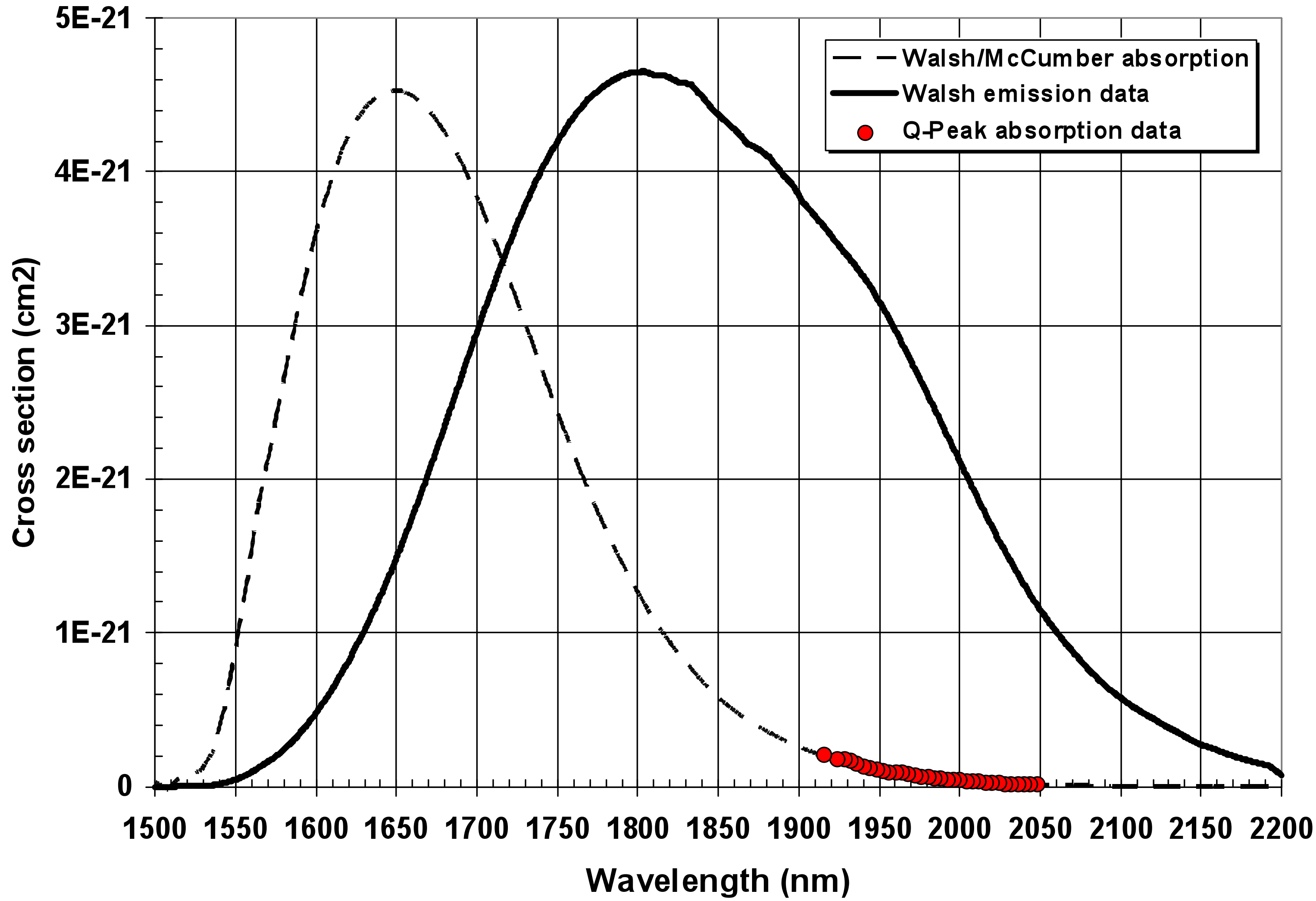
Benjamin M. Cowan



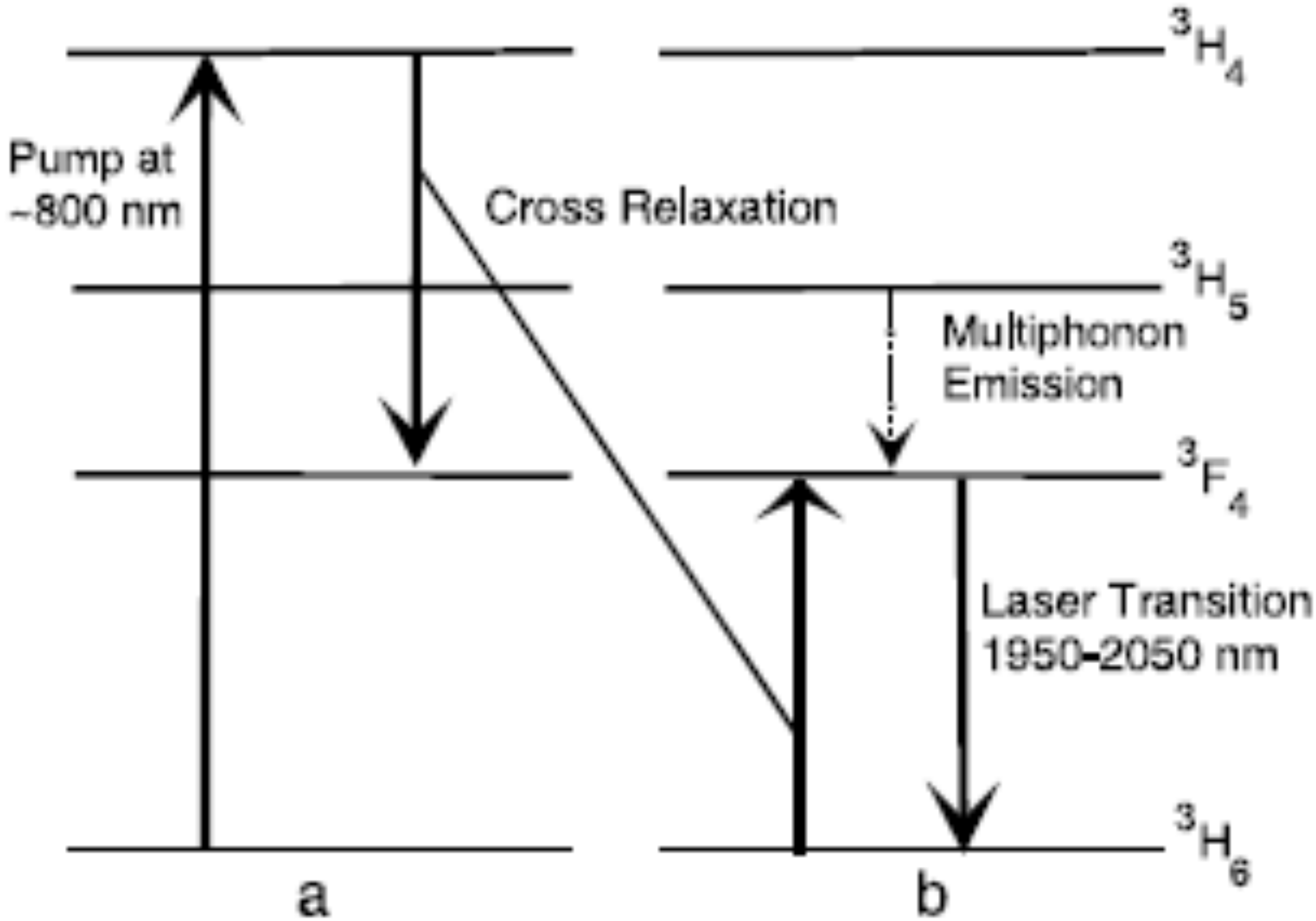
Rare-earth laser transitions used in fiber lasers



Tm:silica has a broad gain cross section



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



fs-duration pulses generated by Tm:silica fiber

June 15, 1996 / Vol. 21, No. 12 / OPTICS LETTERS 881

190-fs passively mode-locked thulium fiber laser with a low threshold

R. C. Sharp, D. E. Spock,* N. Pan,† and J. Elliot†

Raytheon Company, Electronic Systems, 131 Spring Street, Lexington, Massachusetts 02173

Received December 1, 1995

We report a self-starting passively mode-locked thulium-doped silica fiber laser capable of 190-fs pulses. This practical, compact package is driven by a single 50-mW passively cooled diode laser, has a launched pump-power threshold of 18 mW for mode locking, and produces a 50-MHz train of mode-locked 20-pJ pulses at a wavelength near 1.9 μm.

Assume half-gain points at 1925 and 2100 nm → 13 THz linewidth, 33 fs pulses

230-kW peak power femtosecond pulses from a high power tunable source based on amplification in Tm-doped fiber

G. Imeshev and M. E. Fermann

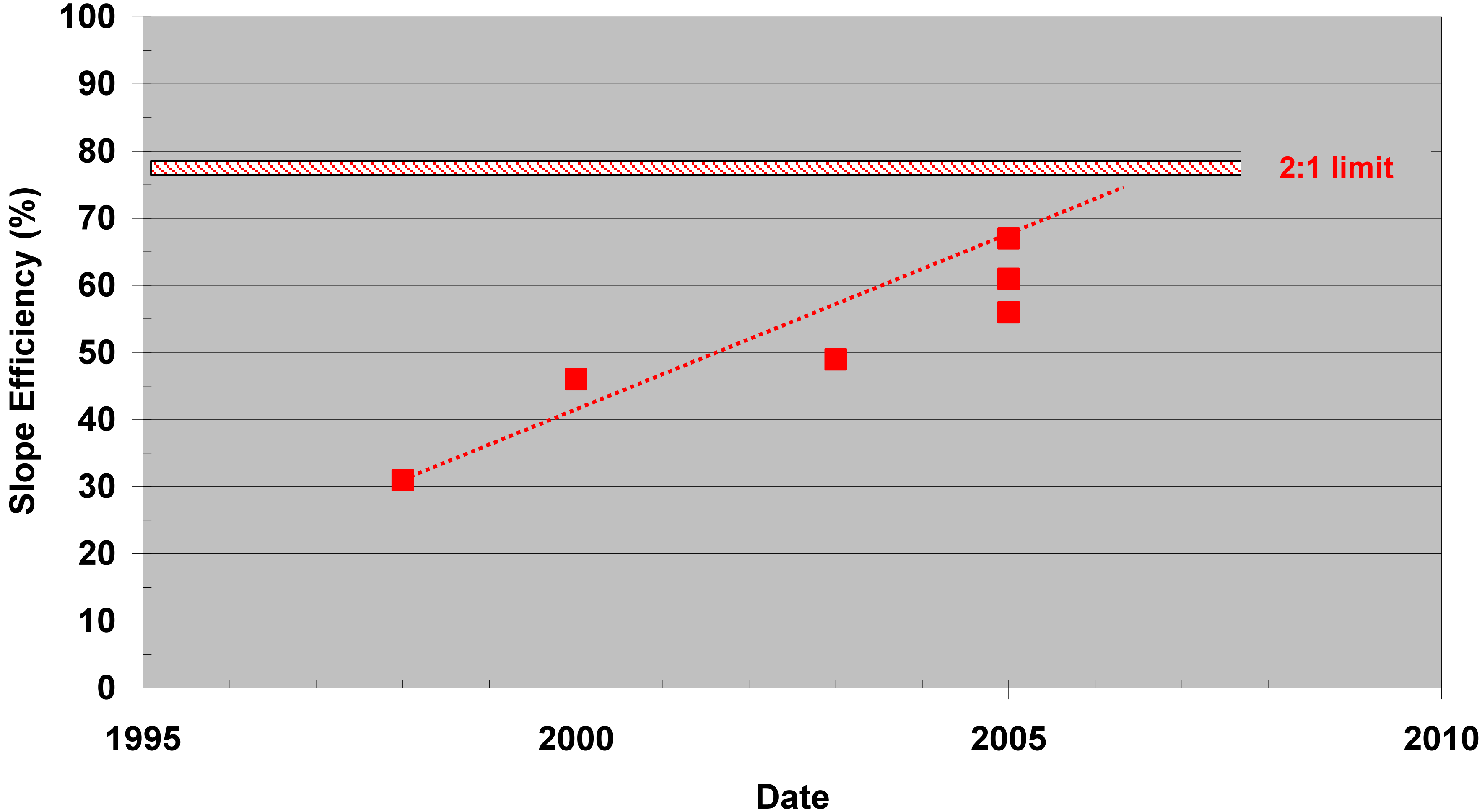
IMRA America, Inc., 1044 Woodridge Ave., Ann Arbor, Michigan 48105, USA
gimeshev@imra.com

Abstract: We report for the first time an all-fiber laser system that generates tunable Watt-level femtosecond pulses at around 2 μm without an external pulse compressor. The system is based on amplification of a Raman shifted Er-doped fiber laser in a Tm-doped 25-μm-core fiber. We obtain 108-fs pulses at 1980 nm with an average power of 3.1 W and a pulse energy of 31 nJ. The peak power at the output of the amplifier is estimated as ~230 kW, which to the best of our knowledge is the highest peak power obtained from a femtosecond or a few-picosecond amplifier based on any doped fiber. The amplified output is frequency-doubled to produce 78-fs pulses at 990 nm with an average power of 1.5 W and a pulse energy of 15 nJ. We demonstrate broad wavelength tunability around 2 μm as well as around 1 μm.

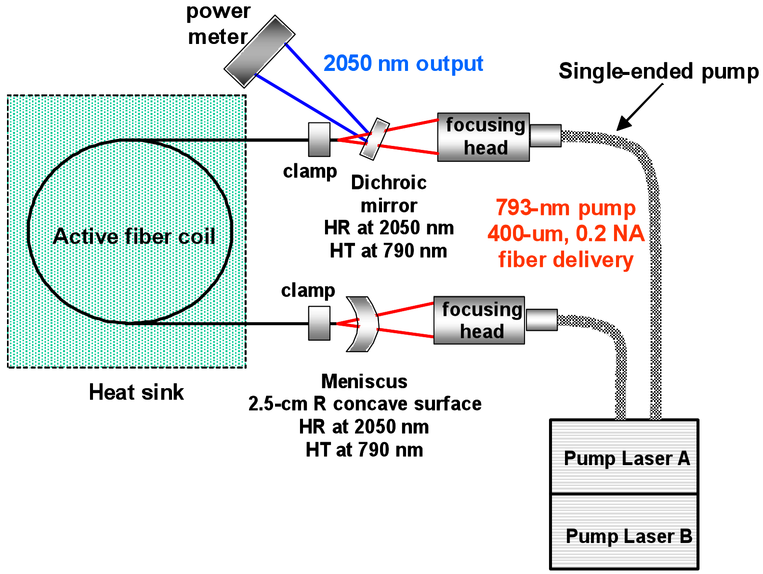
OCIS codes: (140.3510) Lasers, fiber; (320.5520) Pulse compression; (320.7090) Ultrafast lasers.

Received 18 July 2005; revised 31 August 2005; accepted 5 September 2005
19 September 2005 / Vol. 13, No. 19 / OPTICS EXPRESS 7424

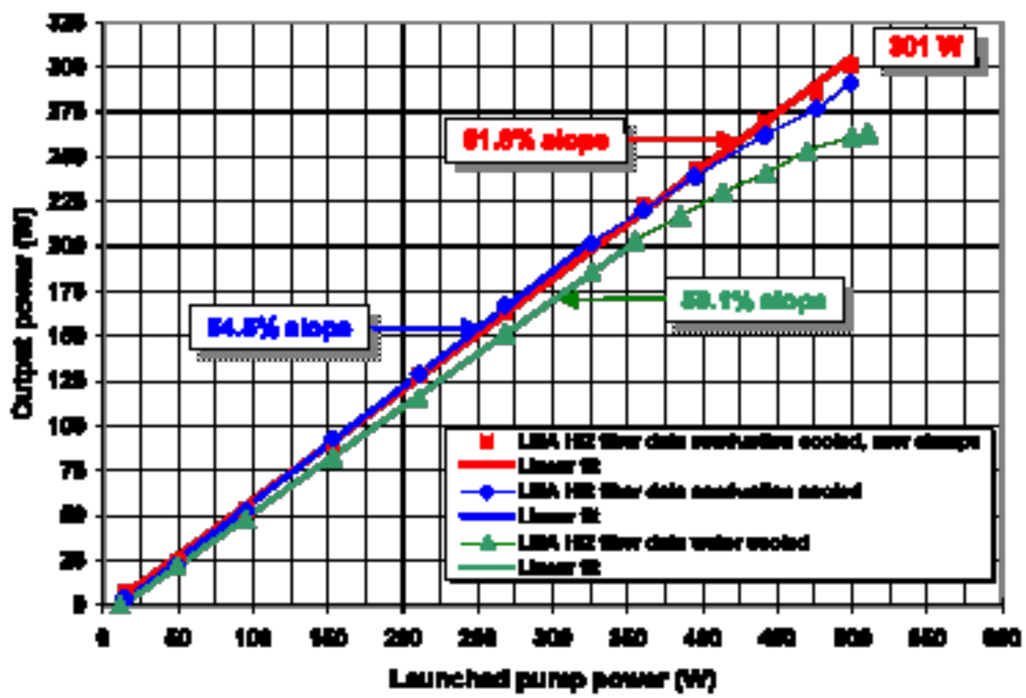
Advances in Tm-doped fiber-laser efficiencies show levels approaching Yb fibers



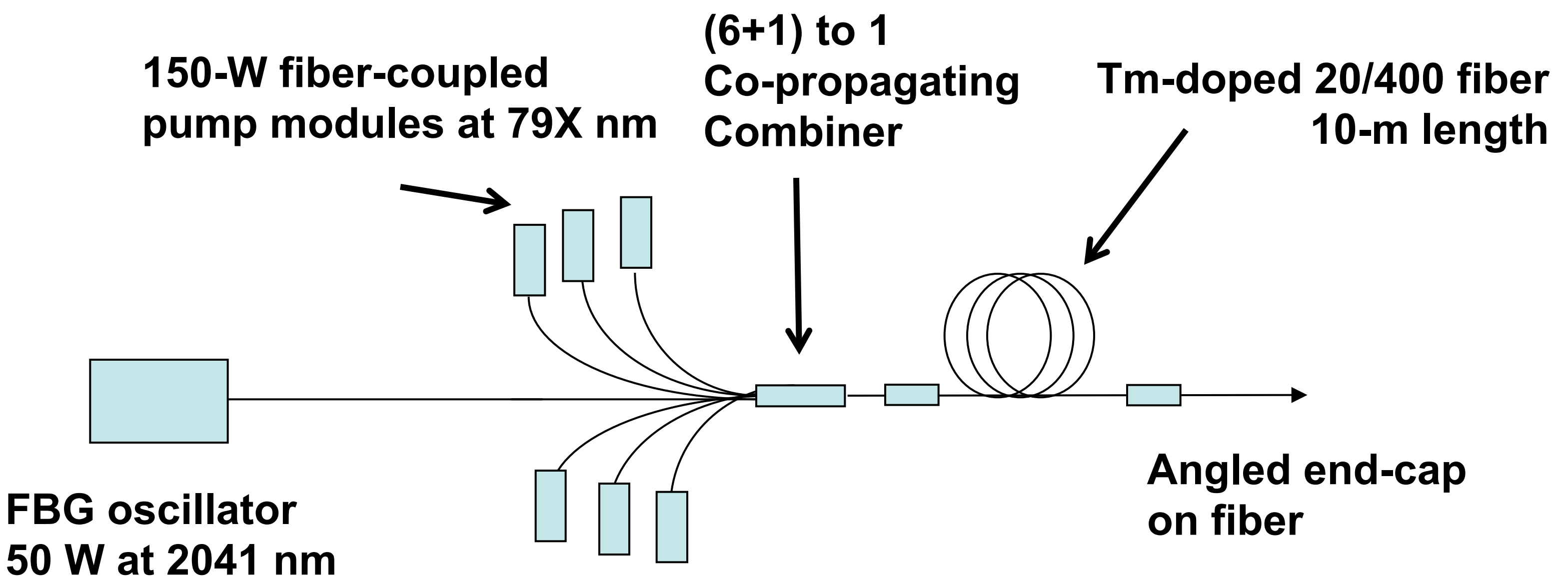
Early Q-Peak results scaling to 300 W, single-mode



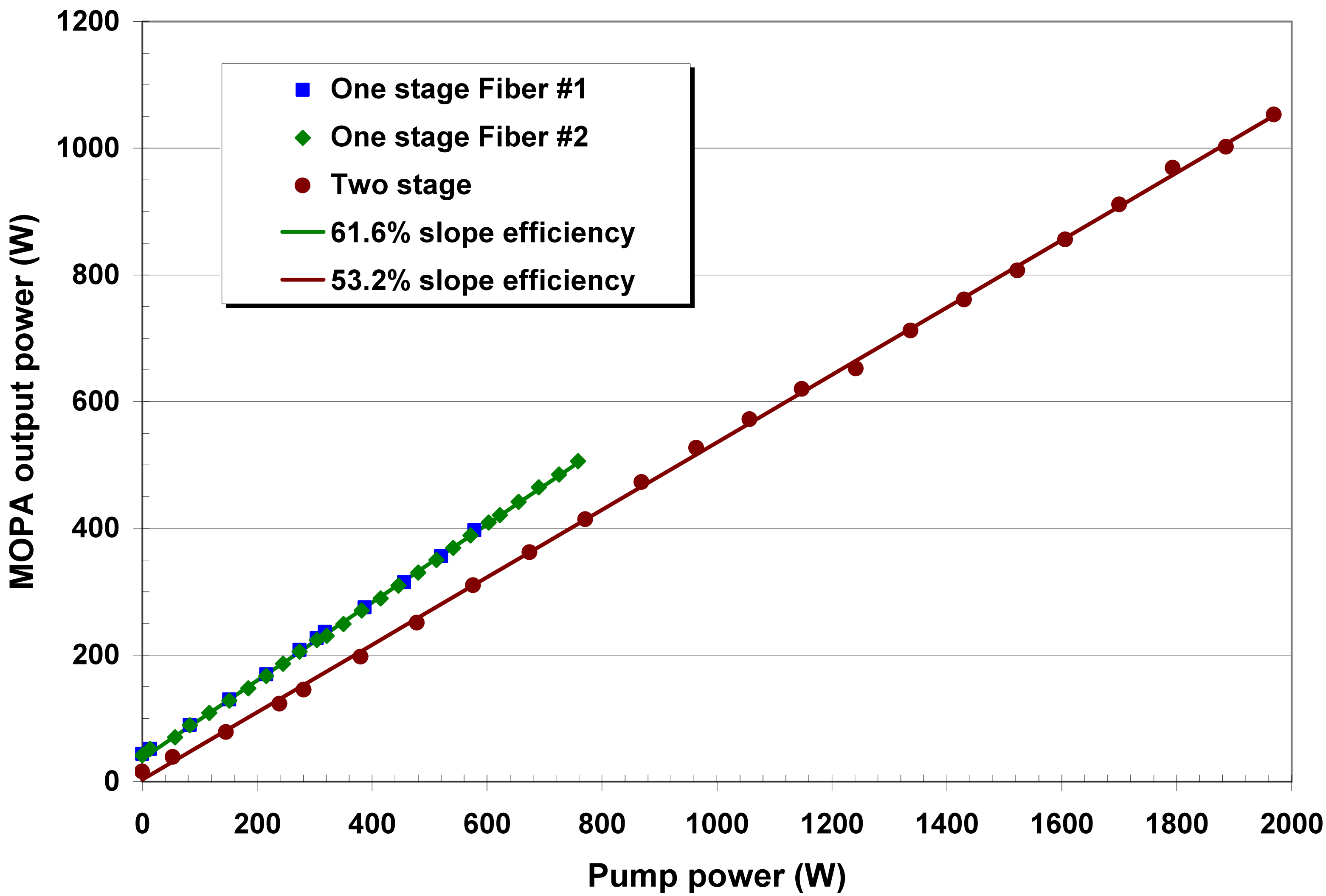
Gain fiber: 5-m long, 3-m undoped ends (2)
Core: 25 µm in diameter, NA: 0.08.
Pump cladding: 400-µm in diameter



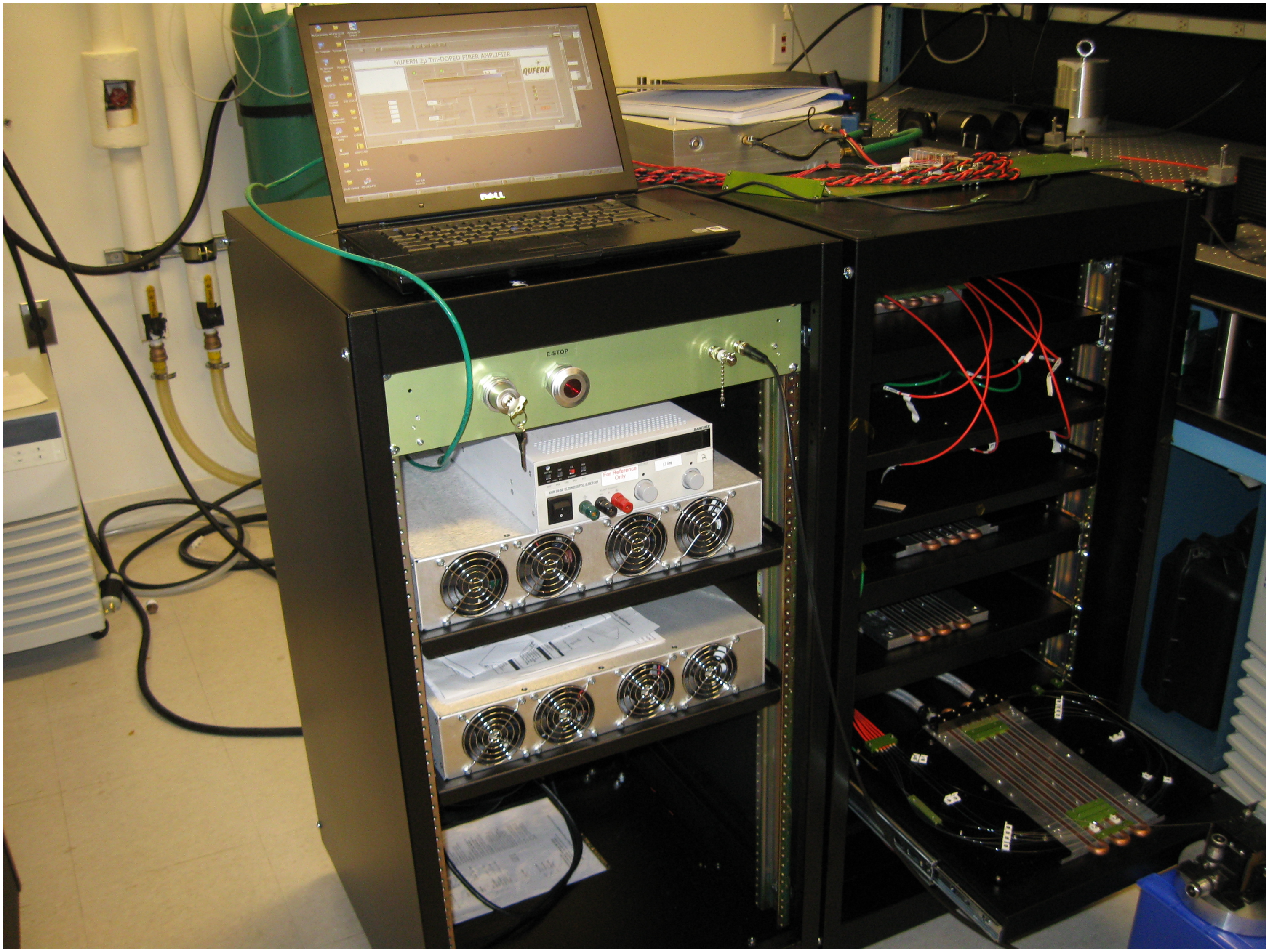
Components for all-glass laser – single stage



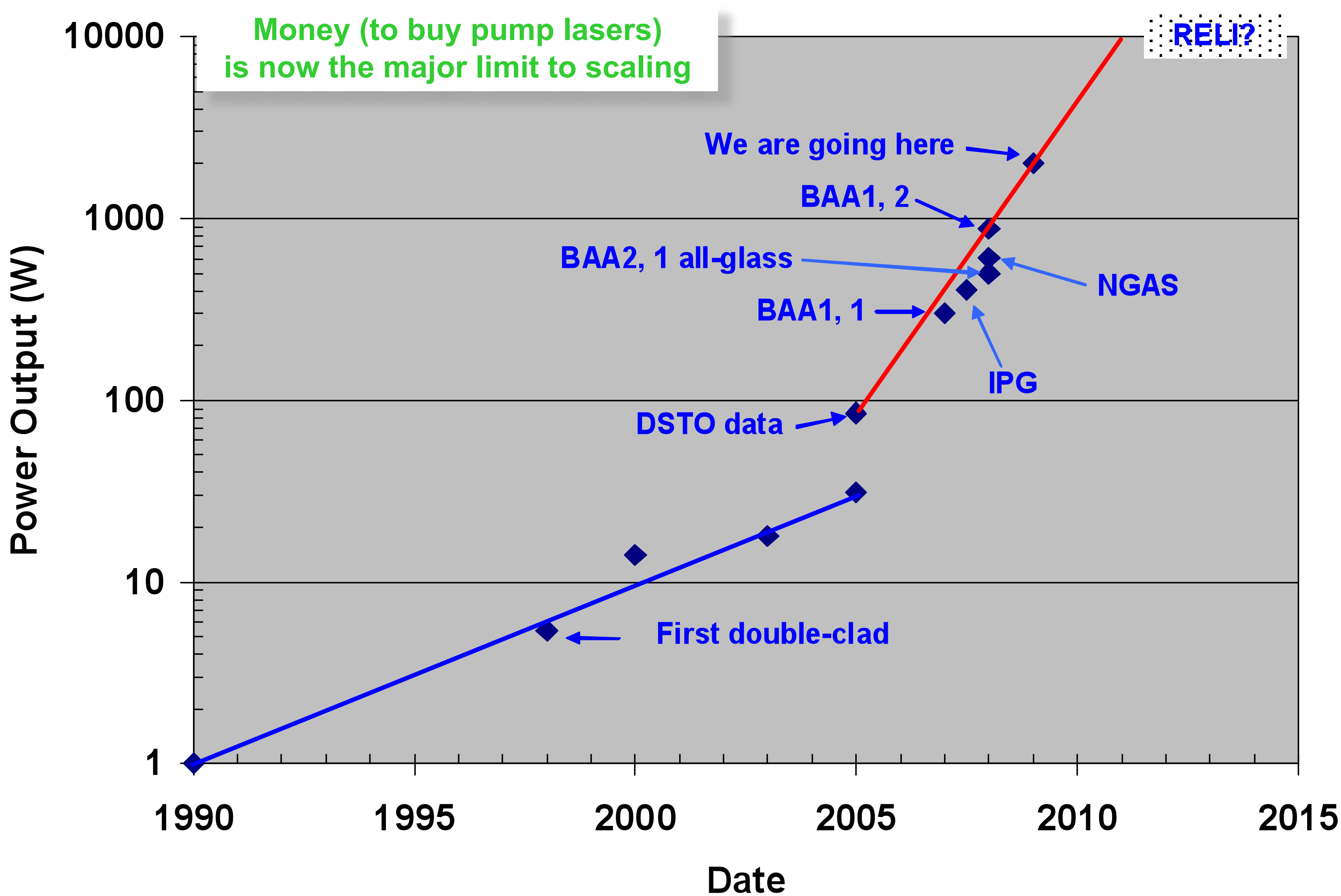
> 1 kW of power output at 2045 nm



Picture of all-glass system



We are now on the same upwards path in power pioneered by Yb-doped fibers



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, nonlinear phase: scales as $1/\lambda$

Brillouin gain (theory): constant in λ

(smaller linewidth ($1/\lambda^2$) cancels smaller gain)

Brillouin gain (actual): reduces with λ

(more sensitive to inhomogeneous effects)

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

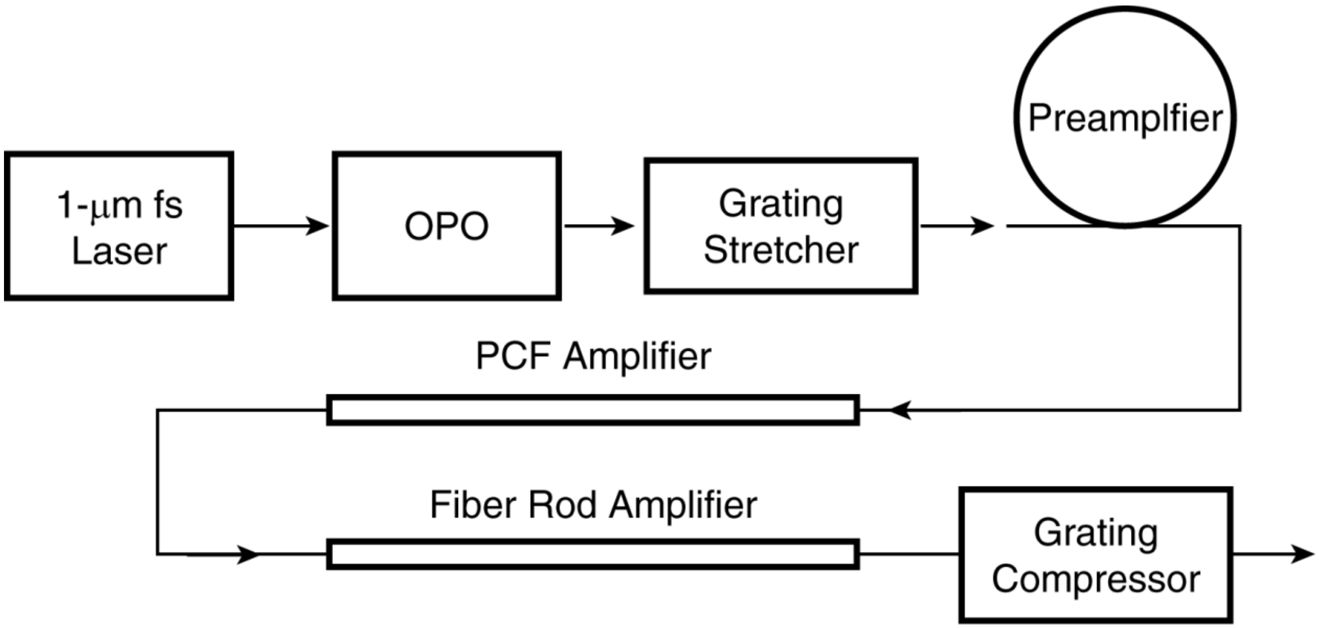
- For the same V parameter, compared to Yb-doped fibers, Tm-doped fibers can have:
  - 8X higher fiber core damage threshold
  - 8X higher stimulated Raman scattering threshold
  - 8X lower nonlinear phase distortion
  - At least 4X higher stimulated Brillouin threshold

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

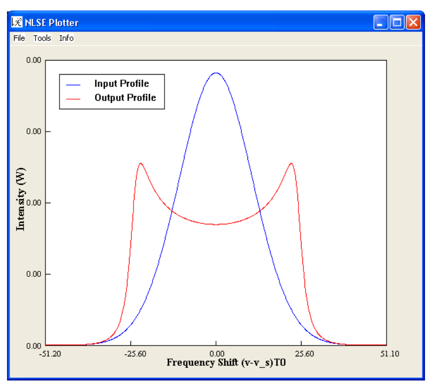
- IPG 10-kW single-mode laser reportedly has about a 30-μm core diameter and is near Raman limit

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

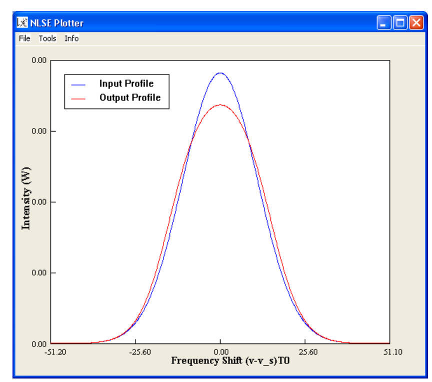
DLA fiber-laser driver uses chirped-pulse amplification to reduce nonlinear effects



8 uJ, 10-ps pulses
1-m fiber length
(0.8 kW average at 100 MHz)
(8 kW average at 1 GHz)



25 um MFD



76 um MFD

Large core (50 um MFD) fibers can allow very high cw powers

Q-peak

Summary

- Solid state lasers are the technology of choice for DLAs
  - Support generation and amplification of ultra-short pulses
  - Have the capability to scale to kW-level powers with high beam quality and acceptable efficiency
- Fiber geometry looks to be the choice for the high-power amplifier stages, based on efficiency and beam quality
- Common solid state lasers operate around a 1-μm wavelength
- To avoid linear and nonlinear absorption, as well as optical breakdown, wavelengths longer than 1 μm are desirable
- The 2-μm -wavelength Tm:fiber laser may be suitable as an efficient high-power source for optical accelerators
  - Large gain-bandwidth supports generation/amplification of short pulses, carrier-phase control is possible
  - Efficiency is enhanced by cross-relaxation pumping process
  - Long wavelength has added advantages in raising the nonlinear limits to power set by the fiber geometry