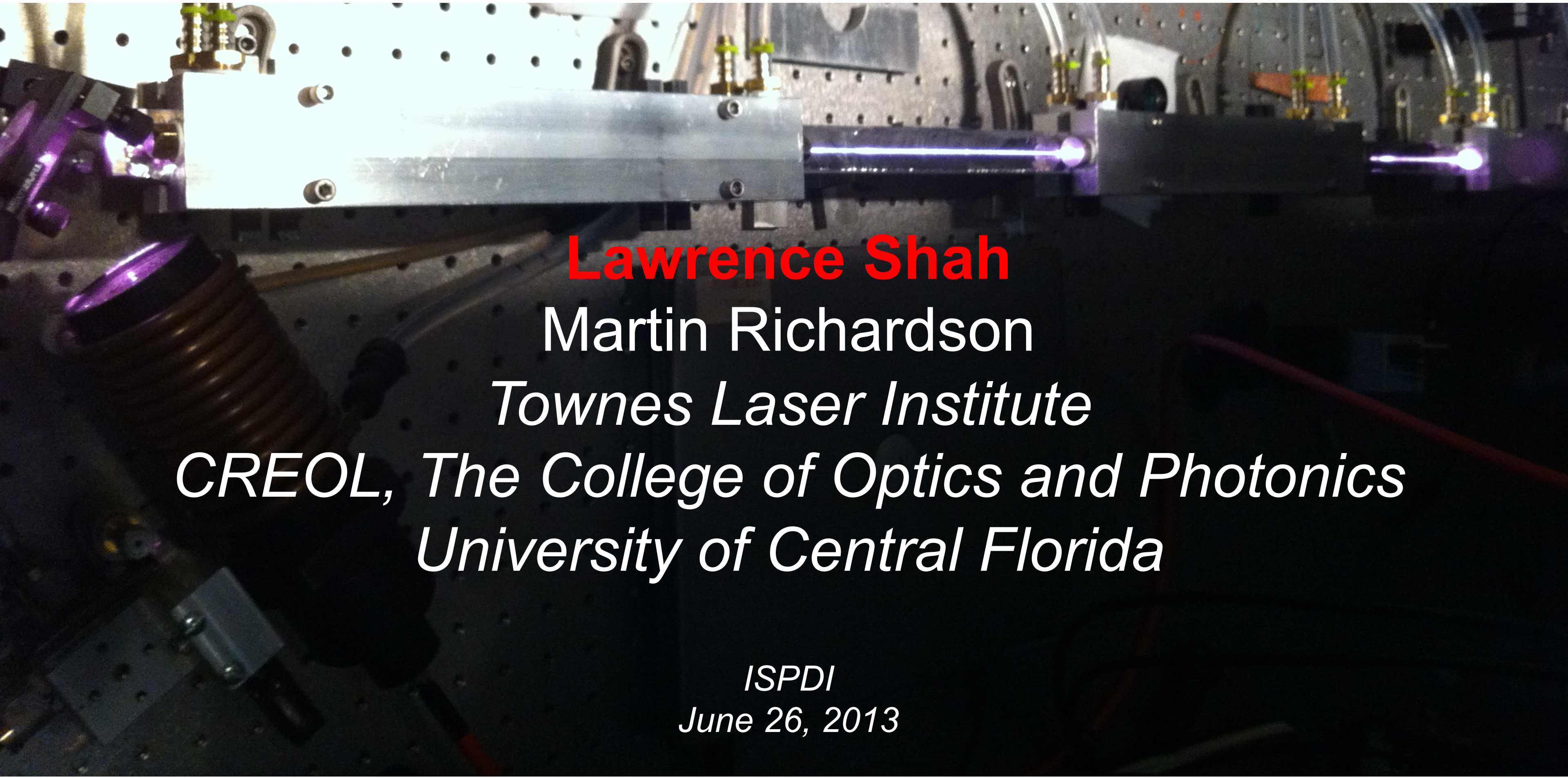
2 µm Fiber Lasers

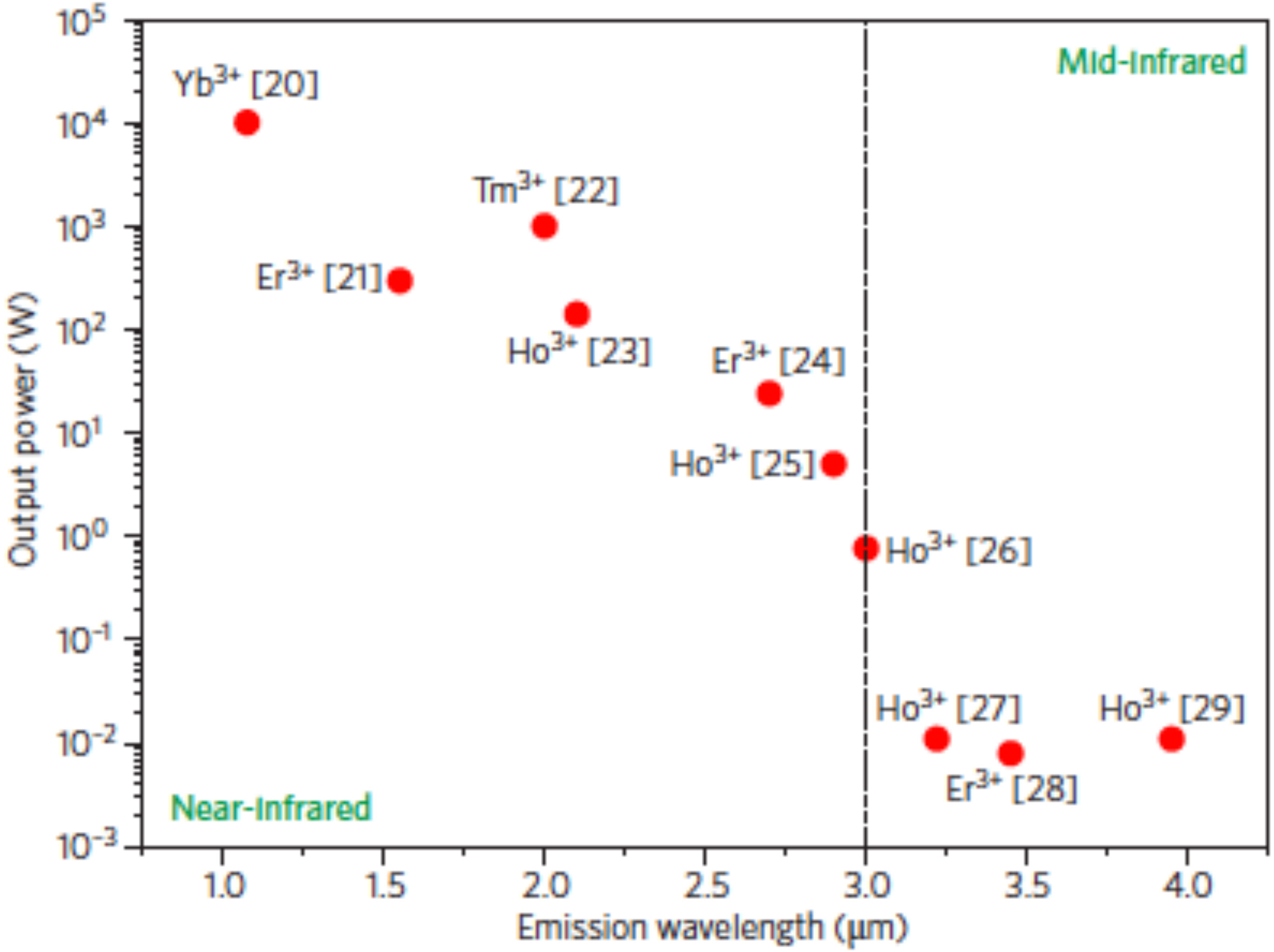


Lawrence Shah
Martin Richardson
Townes Laser Institute
CREOL, The College of Optics and Photonics
University of Central Florida

ISPDI
June 26, 2013

Introduction

Review of near IR to mid IR fiber lasers



S. Jackson, "Towards high-power mid-infrared emission from a fibre laser," Nature Photonics, **6**, 423 (2012)

Introduction

Review of near IR to mid IR fiber lasers

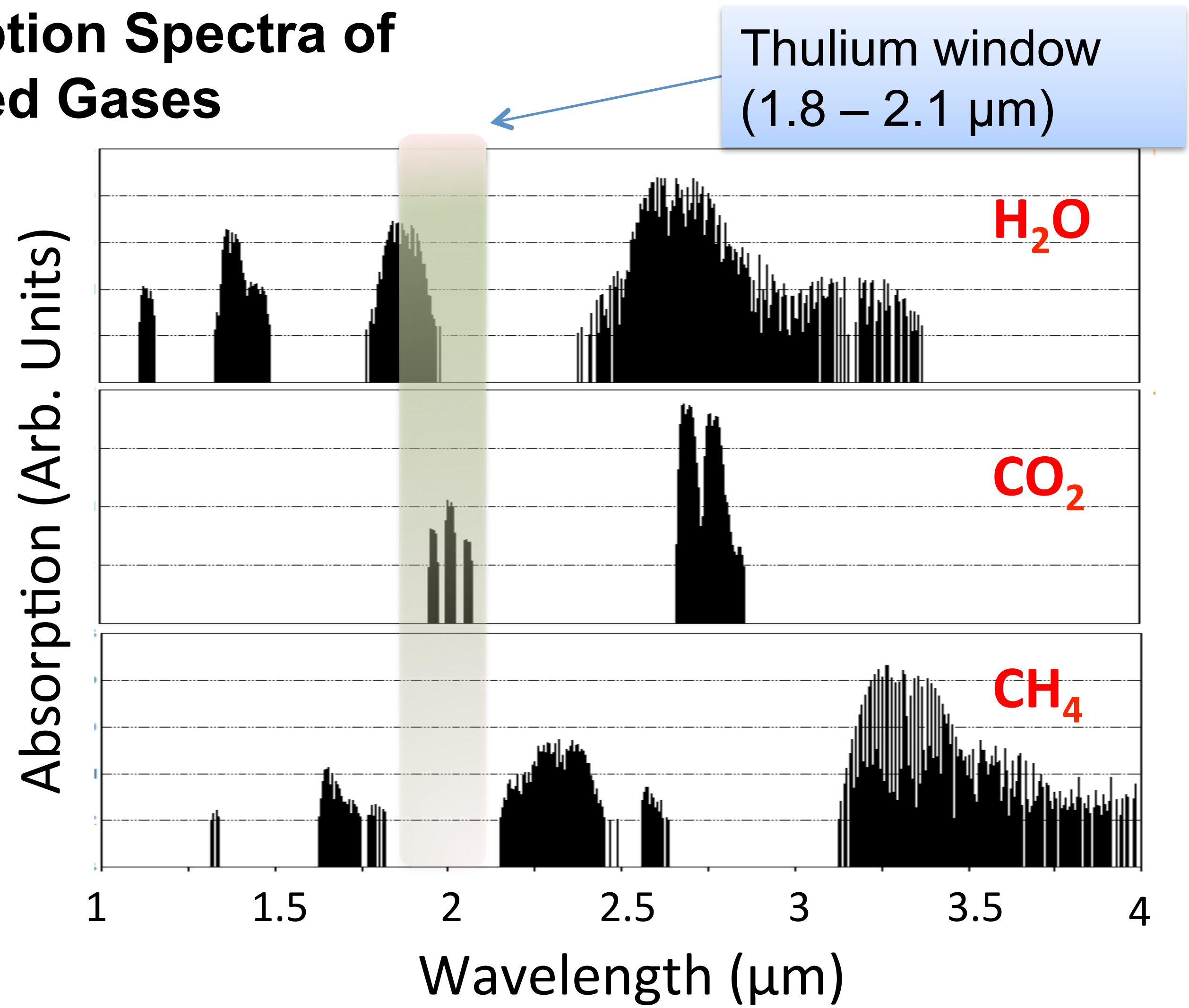
Table B1 | Characteristics of infrared fibre lasers with emission wavelengths ≥1.5 μm.

Dopant(s)	Host glass	Pump λ (μm)	Laser λ (μm)	Transition	Output power (W)	Slope efficiency (%)	Reference
Er^{3+}, Yb^{3+}	Silicate	0.975	1.5	${}^4I_{13/2} \rightarrow {}^4I_{15/2}$	297	19	21
Tm^{3+}, Ho^{3+}	ZBLAN	0.792	1.94	${}^3F_4 \rightarrow {}^3H_6$	20	49	33
Tm^{3+}	Silicate	0.793	2.05	${}^3F_4 \rightarrow {}^3H_6$	1,050	53	22
Tm^{3+}, Ho^{3+}	Silicate	0.793	2.1	${}^5I_7 \rightarrow {}^5I_8$	83	42	34
Ho^{3+}	Silicate	1.950	2.14	${}^5I_7 \rightarrow {}^5I_8$	140	55	23
Tm^{3+}	ZBLAN	1.064	2.31	${}^3H_4 \rightarrow {}^3H_5$	0.15	8	35
Er^{3+}	ZBLAN	0.975	2.8	${}^4I_{11/2} \rightarrow {}^4I_{13/2}$	24	13	24
Ho^{3+}, Pr^{3+}	ZBLAN	1.1	2.86	${}^5I_6 \rightarrow {}^5I_7$	2.5	29	25
Dy^{3+}	ZBLAN	1.1	2.9	${}^6H_{13/2} \rightarrow {}^6H_{15/2}$	0.275	4.5	36
Ho^{3+}	ZBLAN	1.15	3.002	${}^5I_6 \rightarrow {}^5I_7$	0.77	12.4	26
Ho^{3+}	ZBLAN	0.532	3.22	${}^5S_2 \rightarrow {}^5F_5$	0.011	2.8	27
Er^{3+}	ZBLAN	0.653	3.45	${}^4F_{9/2} \rightarrow {}^4I_{9/2}$	0.008	3	28
Ho^{3+}	ZBLAN	0.89	3.95	${}^5I_5 \rightarrow {}^5I_6$	0.011	3.7	29

S. Jackson, "Towards high-power mid-infrared emission from a fibre laser," Nature Photonics, **6**, 423 (2012)

Introduction

Absorption Spectra of Selected Gases

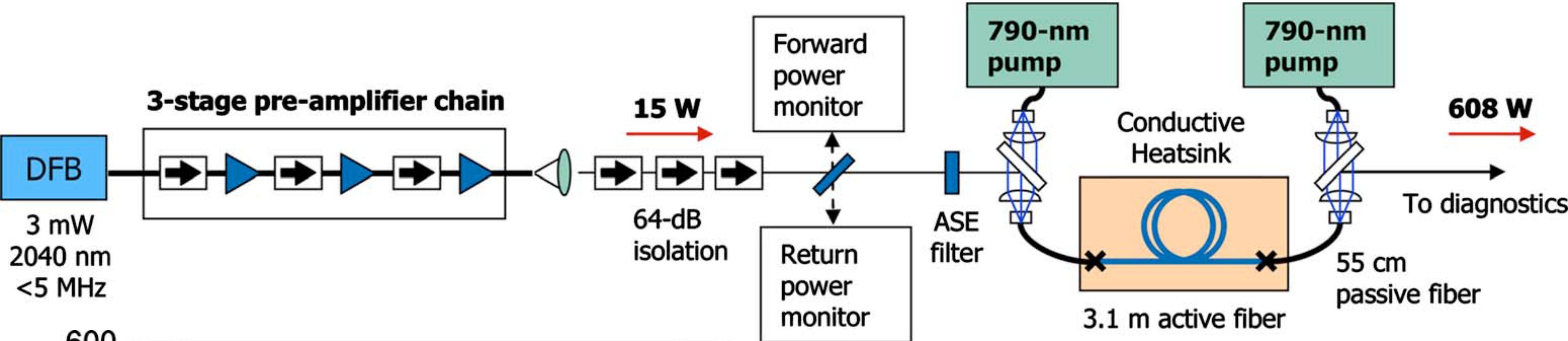


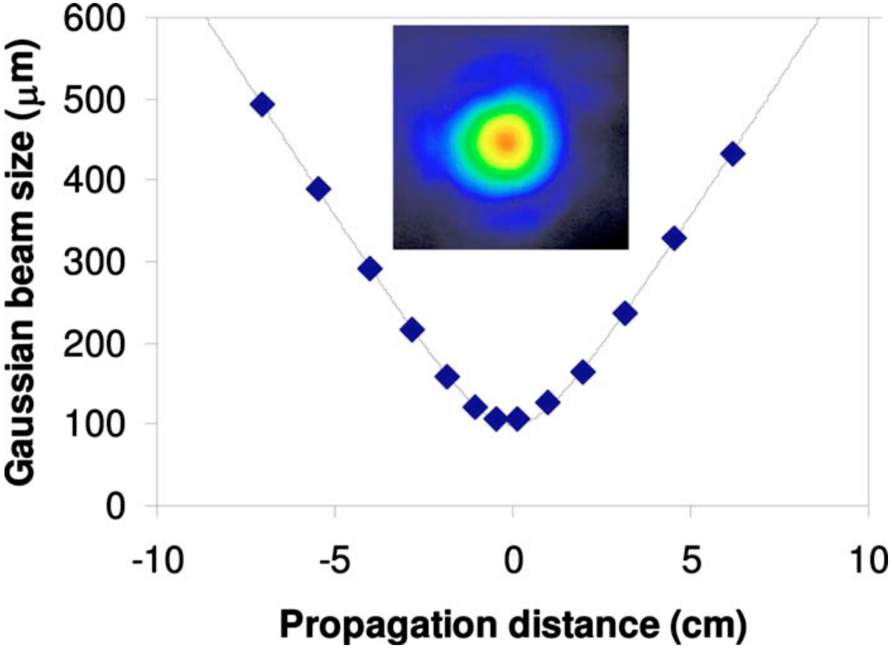
HITRAN2008 line spectrum(http://www.spectralcalc.com)

Outline

- Review of 2 μm fiber laser development
  - CW
  - Pulsed
- Application
  - Nonlinear pump

High power, single frequency

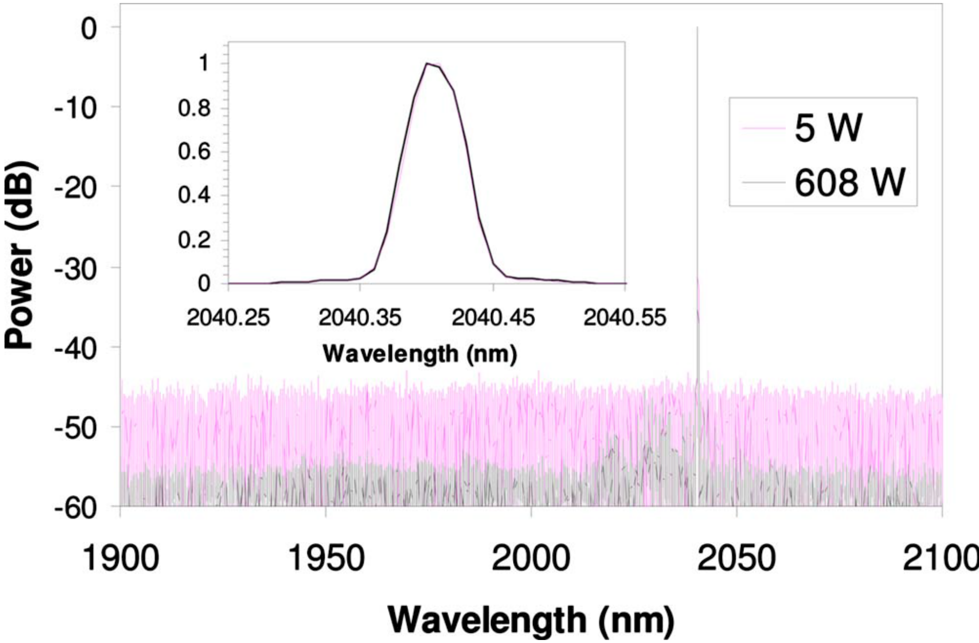


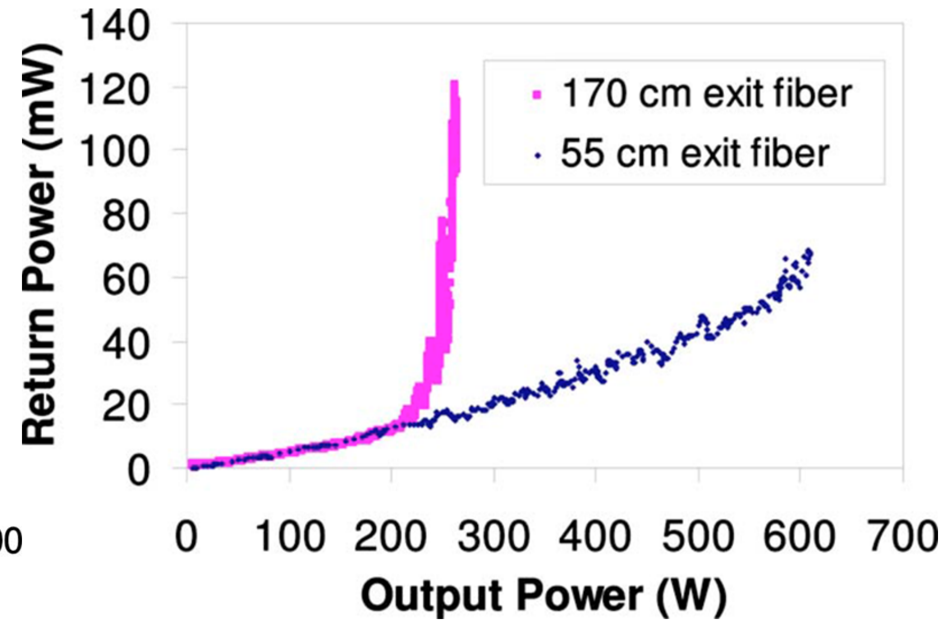


- 790 nm pumping with 54% slope efficiency
- Non-PM LMA Tm fiber 25/400 with 0.08 NA
- $M^2 = 1.05$ at 608 W

G. Goodno et al., "Low –phase-noise, single-frequency, single-mode 608 W thulium fiber amplifier," Opt. Lett. **34**, 1204 (2009)

High power, single frequency

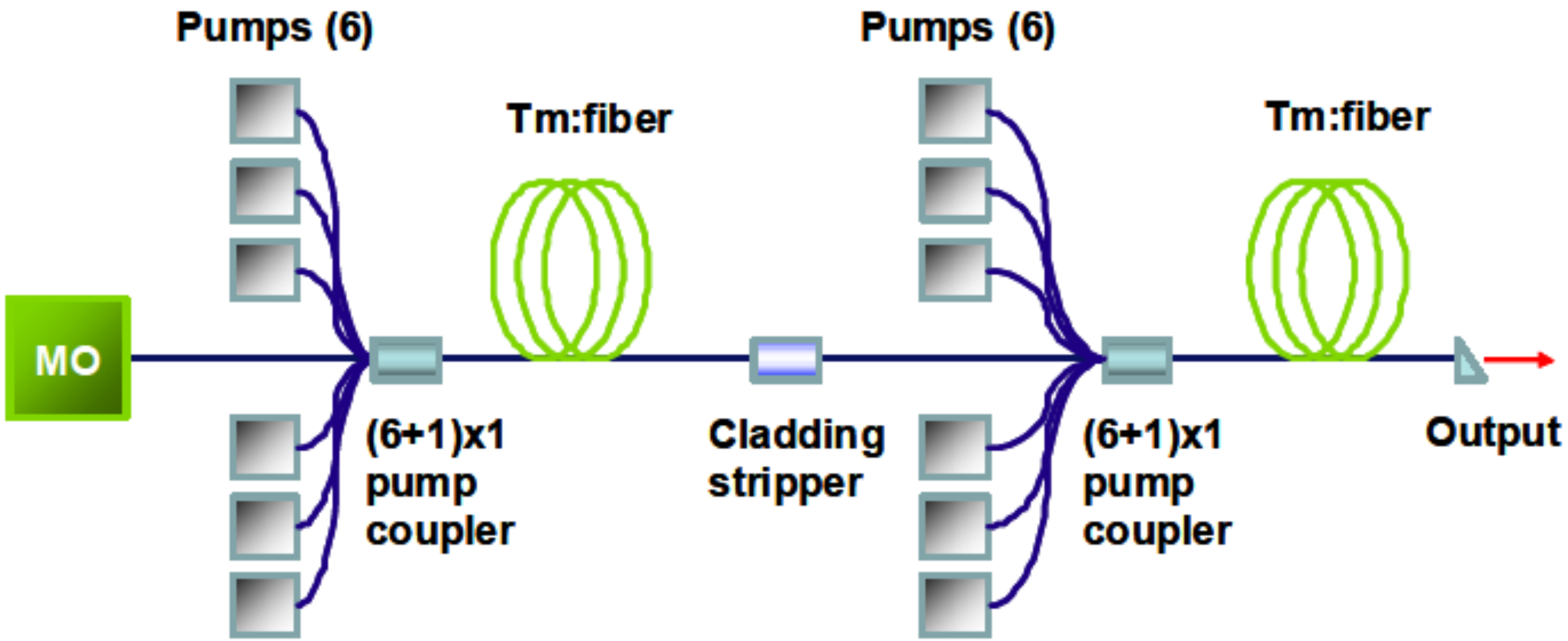




- <5 MHz linewdith maintained with <0.4% of total power in ASE
- High power single-mode and single-frequency output achieved by suppression of SBS
- Low phase noise and high quality output ideal for coherent beam combining

G. Goodno et al., "Low –phase-noise, single-frequency, single-mode 608 W thulium fiber amplifier," Opt. Lett. **34**, 1204 (2009)

All-fiber 1 kW Tm Laser



MO

50 Watts at 2045-nm

1st Stage

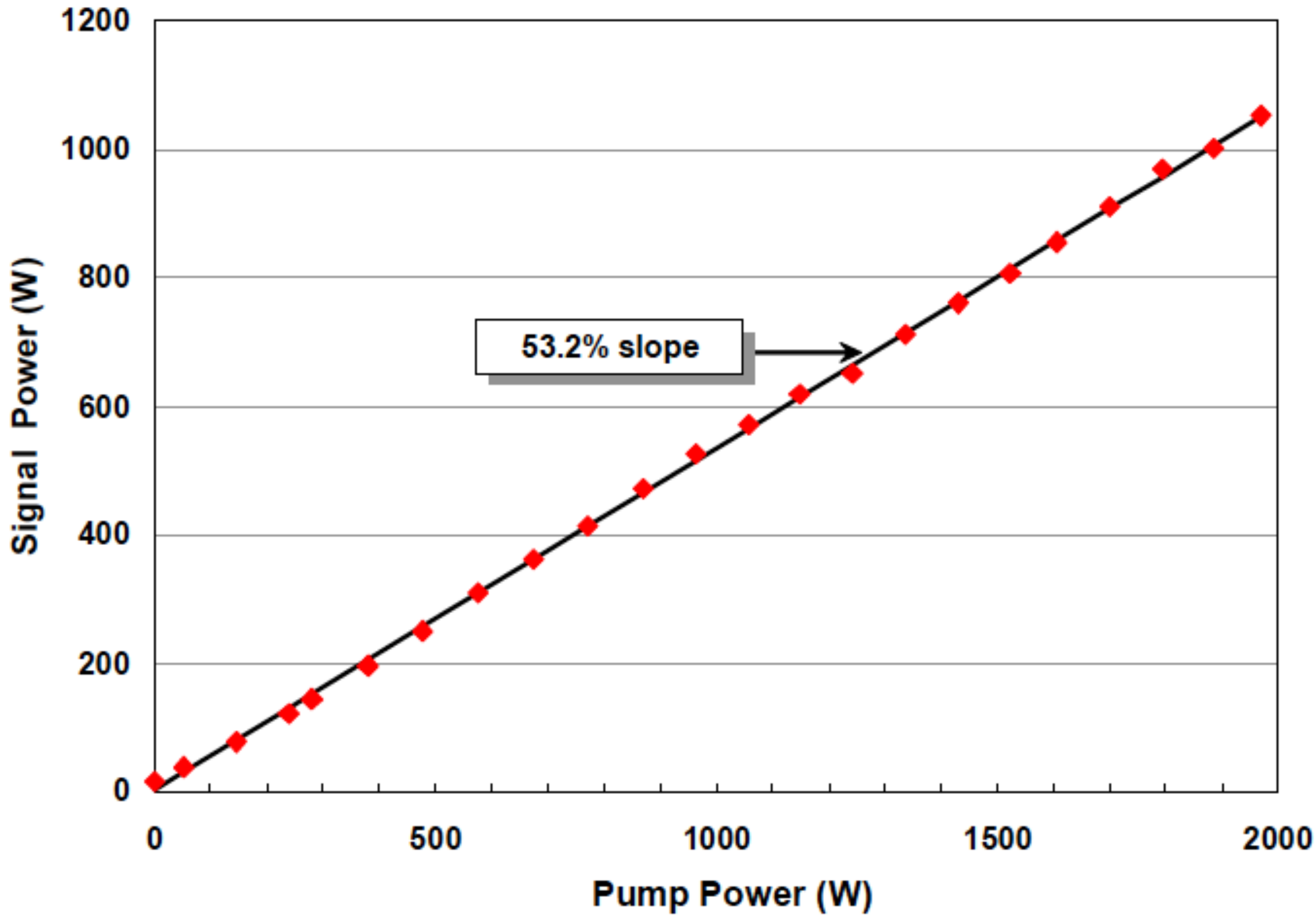
12m LMA-TDF-20/400 active fiber

2nd Stage

12m LMA-TDF-20/400 active fiber

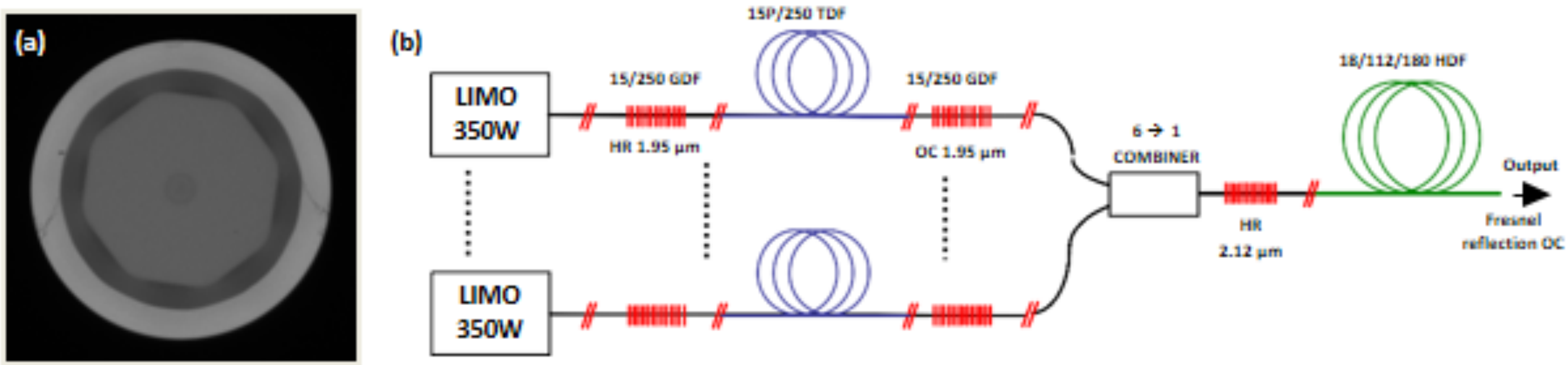
T. Ehrenreich et al., “1-kW all-glass Tm:fiber laser,” Proc. SPIE 7580-112 (2010)

All-fiber 1 kW Tm Laser



T. Ehrenreich et al., “1-kW all-glass Tm:fiber laser,” Proc. SPIE 7580-112 (2010)

All-fiber 400 W Ho Laser



The pump is 6 Tm:fiber lasers at 1.95 µm (160-180 W each)

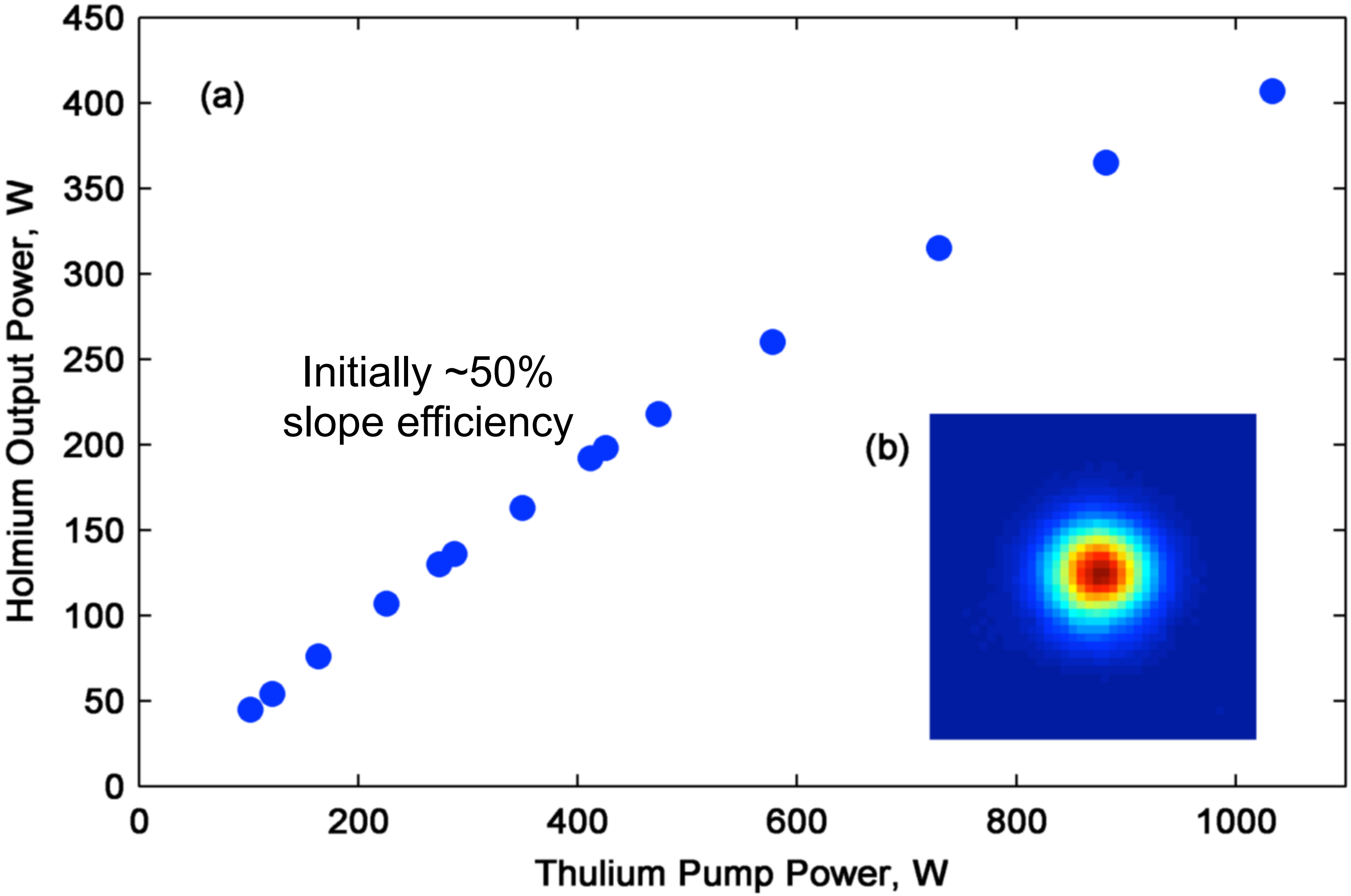
Tm:fiber 15 µm core, 0.1 NA,, 25 µm pedestal

Ho:fiber 18 µm core, 0.08 NA, 112 µm octagonal cladding

V-parameter 2.2 ensures robust single-mode output

A. Hemming et al., “A monolithic cladding pumped holmium-doped fibre laser,” CLEO CW1M.1 (2013)

All-fiber 400 W Ho Laser



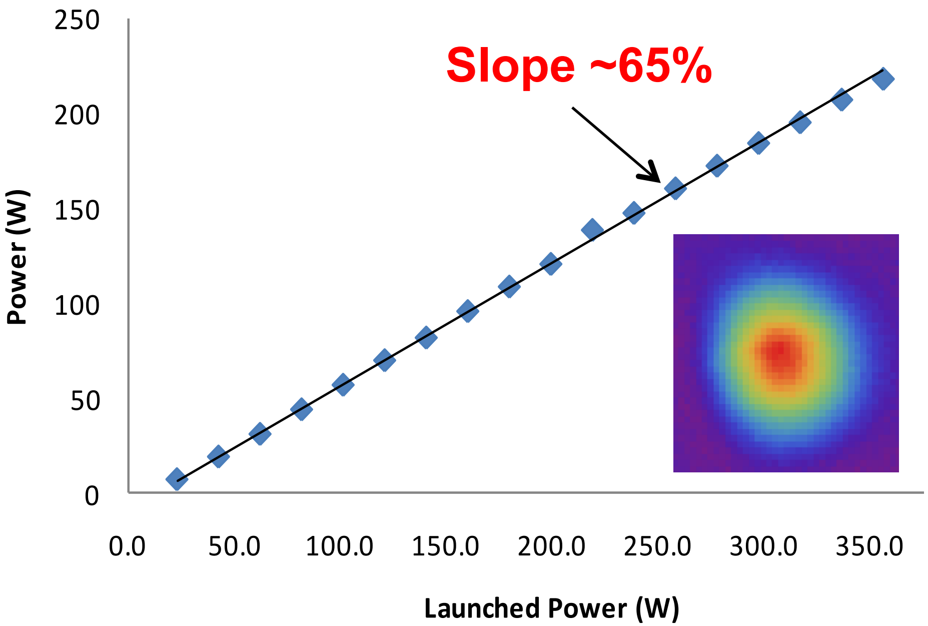
A. Hemming et al., “A monolithic cladding pumped holmium-doped fibre laser,” CLEO CW1M.1 (2013)

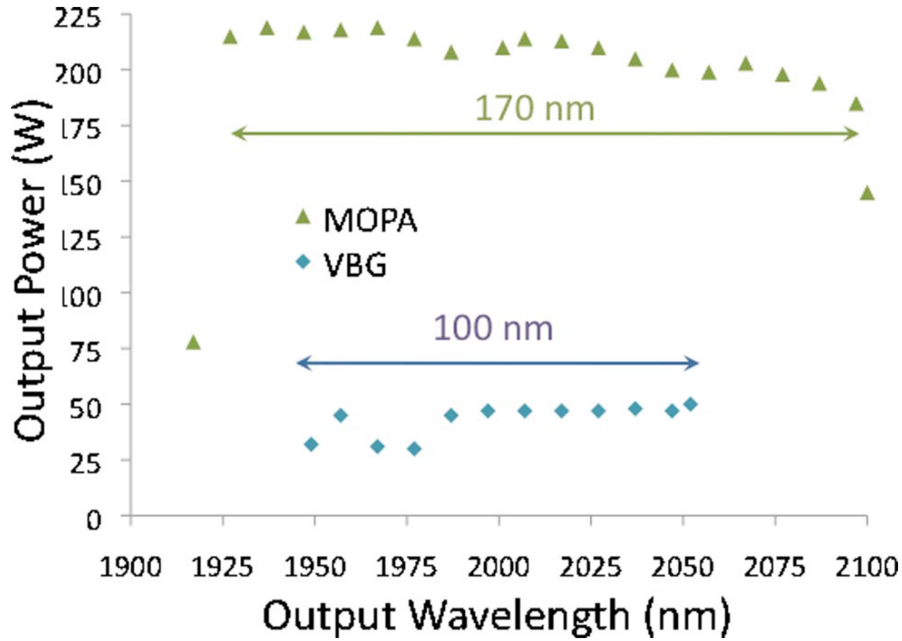
Tm:fiber Tuning Range

W. A. Clarksom et al., “High-power cladding-pumped Tm-doped silica fiber laser with wavelength tuning from 1860 to 2090 nm,” Opt Lett. 27, 1989 (2002).

- 216 W maximum output
- 60% amplifier optical-to-optical efficiency
- 790 nm diode pumping

- >200 W from 1927-2097 nm
- <200 pm linewidth
- Nearly diffraction-limited

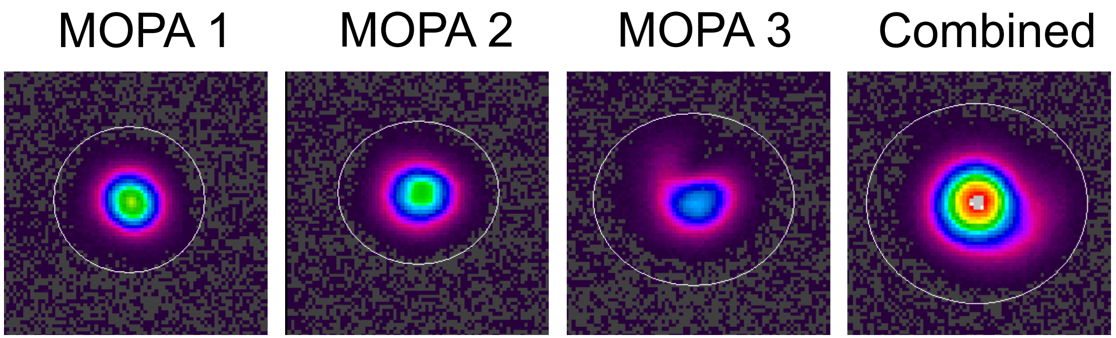


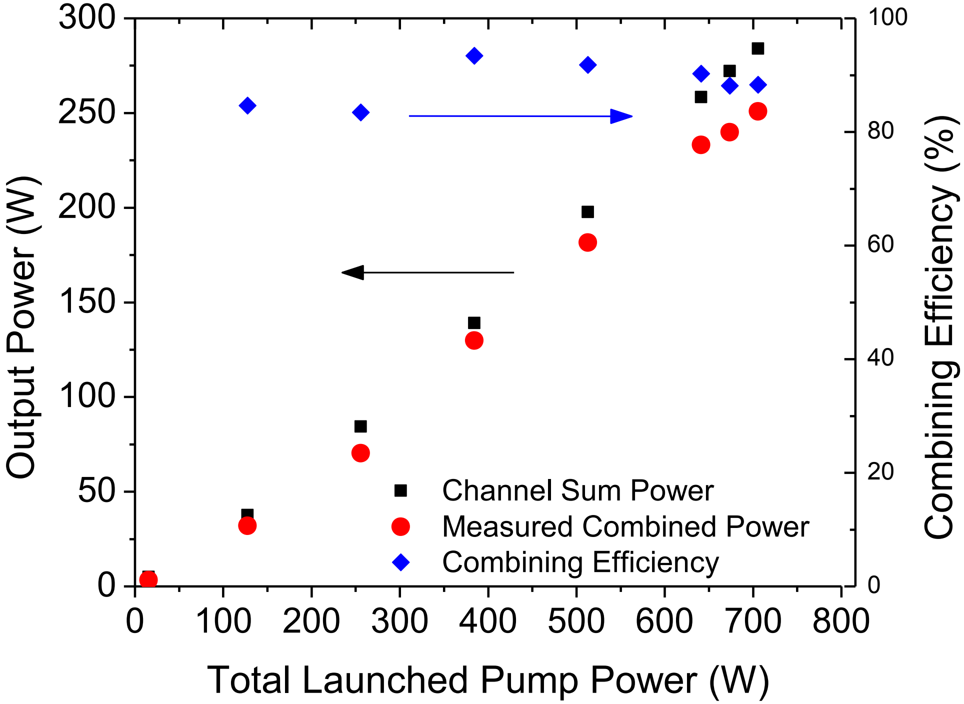


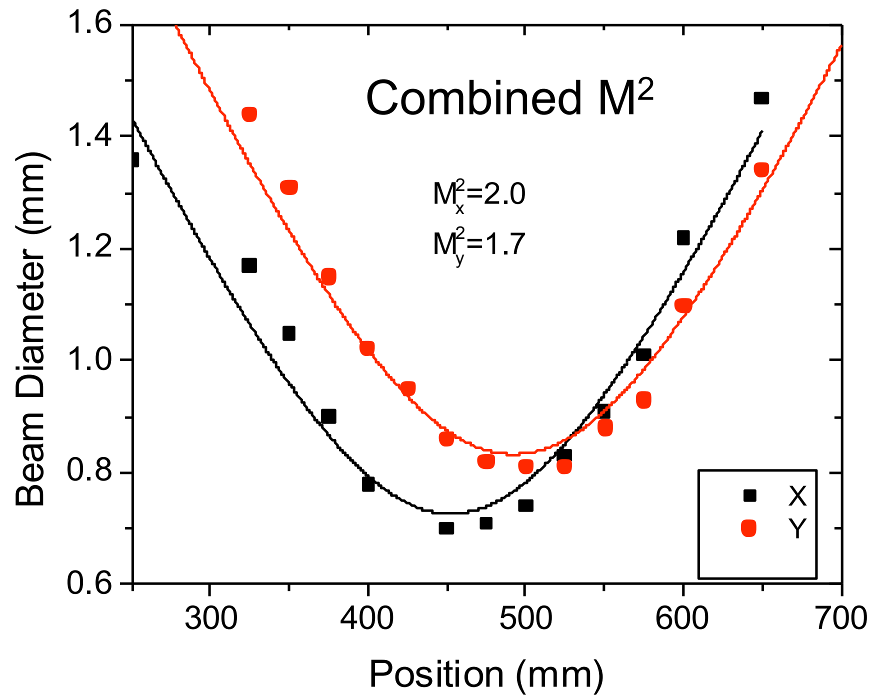
T.S. McComb, et al, "High-power widely tunable thulium fiber lasers," Appl. Opt. **49**, 6236 (2010)

Tm:fiber SBC Results

MOPA 1: 2046 nm, 87W
MOPA 2: 2040 nm, 99 W
MOPA 3: 2035 nm, 98 W







89% combining efficiency, 35% total optical-to-optical efficiency
Incident Power 284 W, combined power 253 W

CW Summary

- Tm and Ho fiber development have achieved 1 kW and 400 W average power respectively with nearly diffraction-limited beam quality
- Component availability and performance improving
- Power scaling is primarily limited by heat, in particular Ho:fiber is far from theoretical efficiency
- Doped glass chemistry is a challenge

Outline

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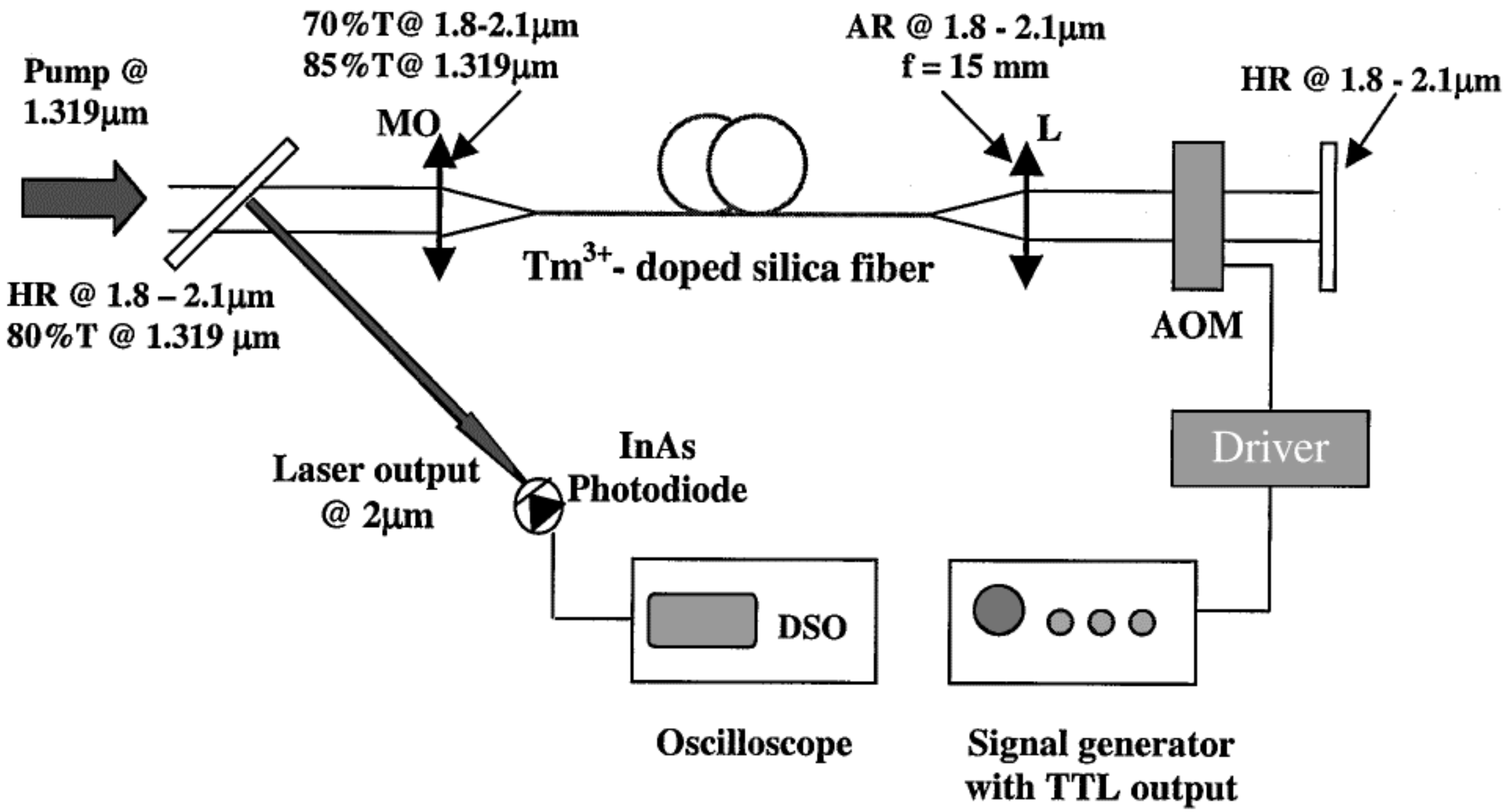
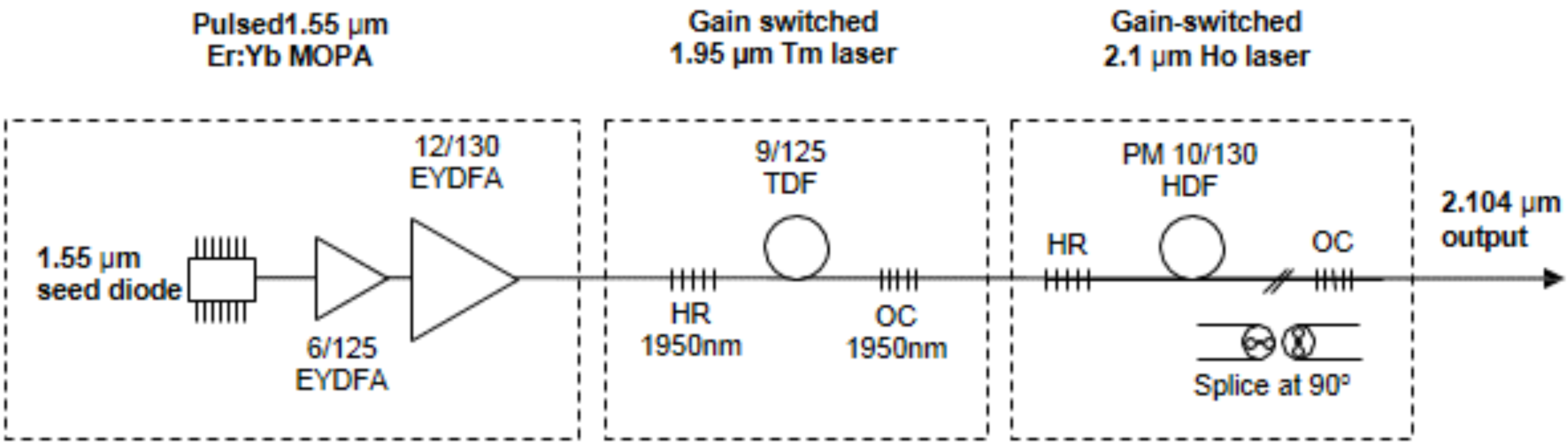
Q-switch Oscillator



Generated 0.6 mJ pulses with 150 ns pulse duration at 100 Hz

A. F. El-Sherif and T. A. King, "High-peak-power operation of a Q-switched Tm^{3+}-doped silica fiber laser operating near 2 μm," Opt. Lett. **28**, 22 (2003)

Gain switched nanosecond



Ho:fiber output 16 µJ energy, 85 ns duration at 600 kHz
>60% slope efficiency, M^2 <1.1

A.Hemming et al., "Development of resonantly cladding-pumped holmium-doped fibre lasers," SPIE Proceedings 8237, paper 82371J (2013)

This method can be used to produce 10 ns pulses directly without the need for active modulators at 2 µm

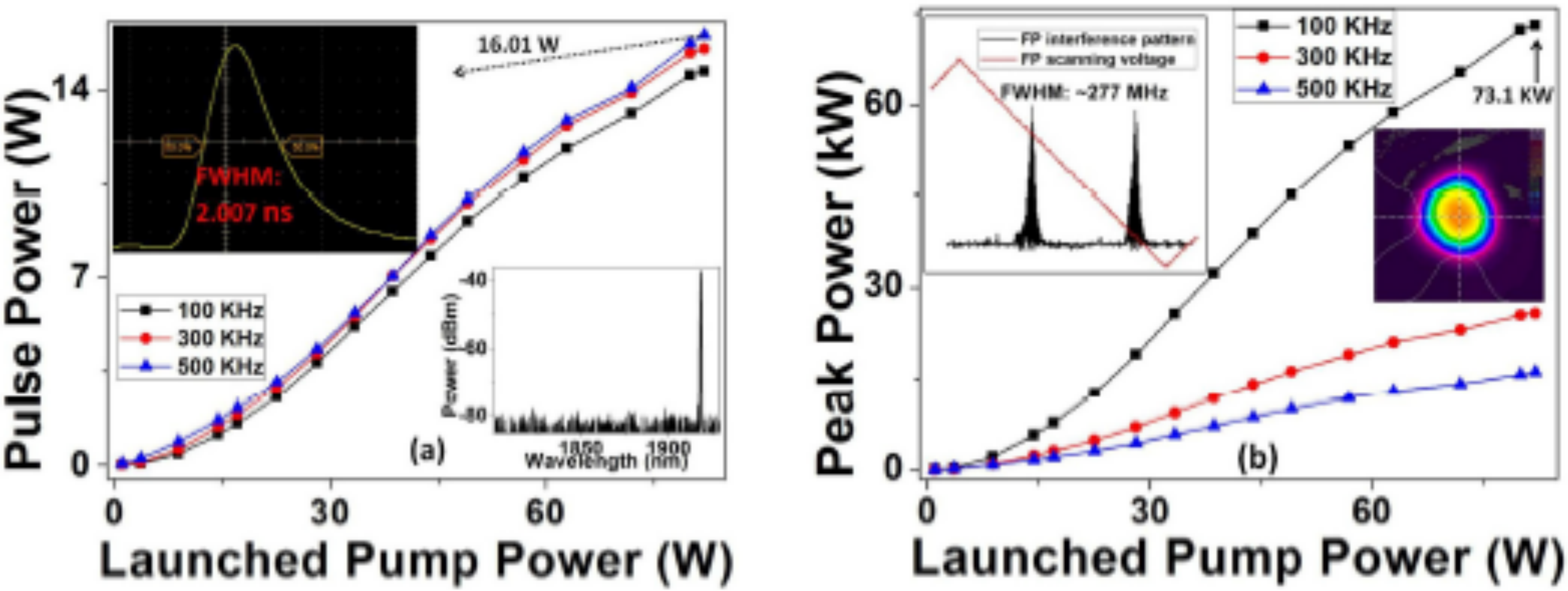
M. Jiang and P. Tayebati, "Stable 10 ns, kilowatt peak-power pulse generation from a gain-switched Tm-doped fiber laser," Opt. Lett. 32, 1797–1799 (2007).

Narrow linewidth nanosecond Tm:fiber lasers

Primarily for LIDAR applications, several efforts to develop high peak power Tm:fiber "single-frequency" sources

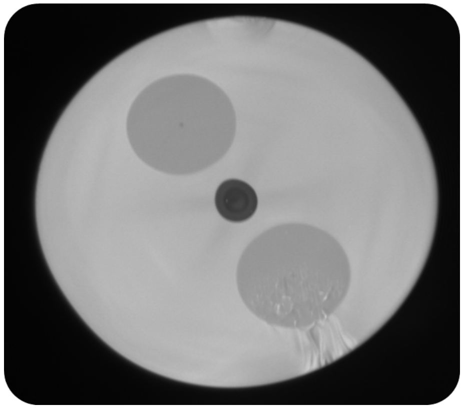
J. Geng et al., "Kilowatt-peak-power, single-frequency, pulsed fiber laser near 2 μm," Opt. Lett. **36**, 2293 (2011)

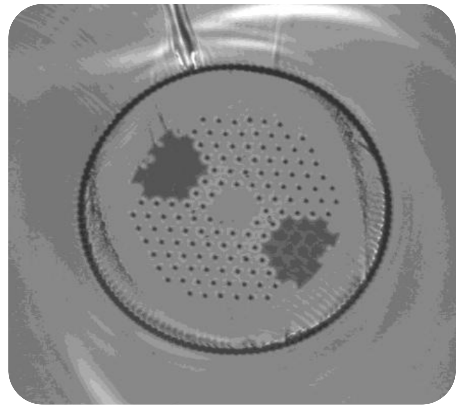
W. Shi et al., "220 μJ monolithic single-frequency Q-switched fiber laser at 2 μm by using highly Tm-doped germanate fibers," Opt. Lett. **36**, 3375 (2011).

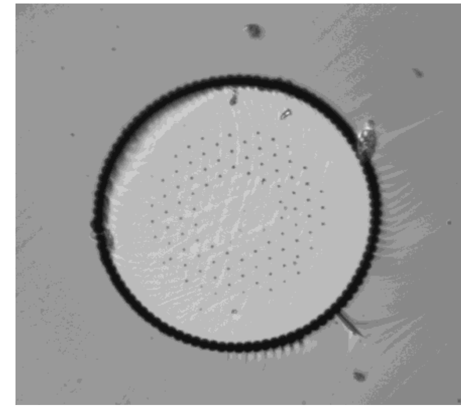


Q. Fang et al., "High power and high energy monolithic single frequency 2 μm nanosecond pulsed fiber laser by using large core Tm-doped germanate fibers: experiment and modeling," Opt. Ex. **20**, 16410 (2012)

Comparison of Tm-doped LMA Fibers







Fiber	LMA 25/400	Flexible PCF 50/250	PCF Rod 80/220
Length	3 m	3 m	1.5 m
Mode field diameter	23 µm	36 µm	56 µm
Numerical aperture	0.1	0.04	0.03
Mode field area	~400 μm^2	~1000 μm^2	~2500 μm^2

CW lasing in Tm:PCF

N. Modsching et al., "Lasing in thulium-doped polarizing photonic crystal fiber," Opt. Lett. **36**, 3873 (2011)

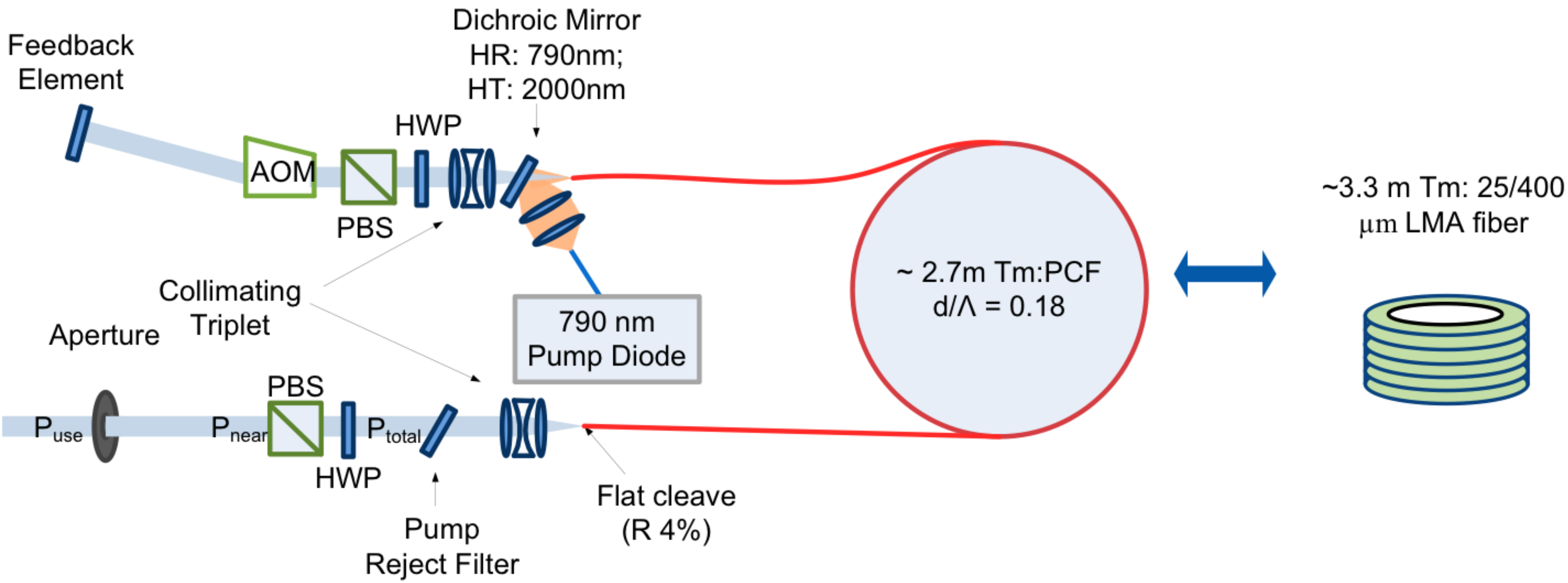
Q-switched Tm:PCF oscillator

P. Kadwani et al., "Q-switched thulium-doped PCF laser," Opt. Lett. **37**, 1664-1666 (2012)

CW lasing in Tm:PCF rod

C. Gaida et al., "Lasing in thulium-doped rod-type PCF," Opt. Lett. **37**, 4513 (2012)

Comparison of Tm-doped LMA Fibers

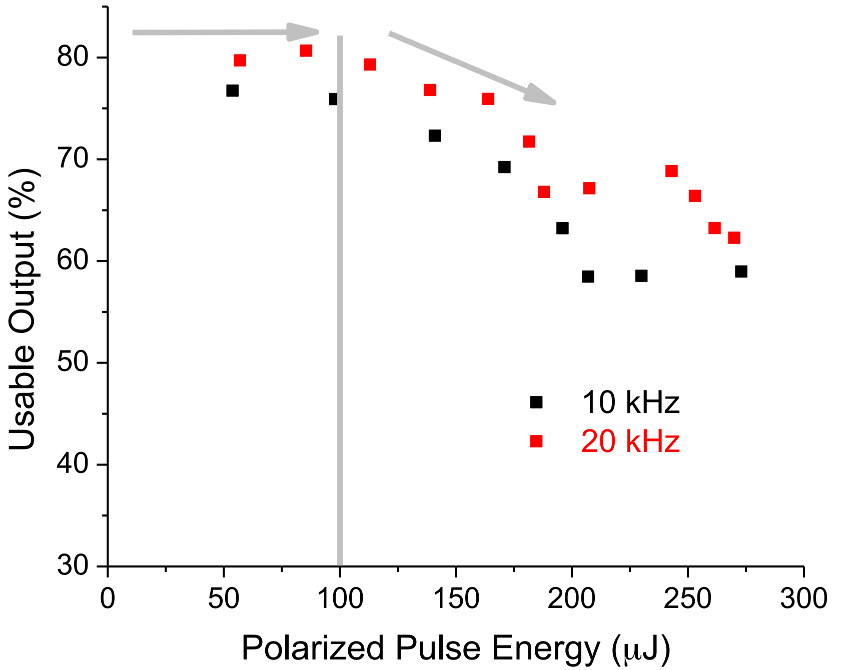


C.C.C. Willis et al., "High energy Q-switched Tm^{3+}-doped polarization maintaining silica fiber laser," Photonics West 2010, paper 75801F

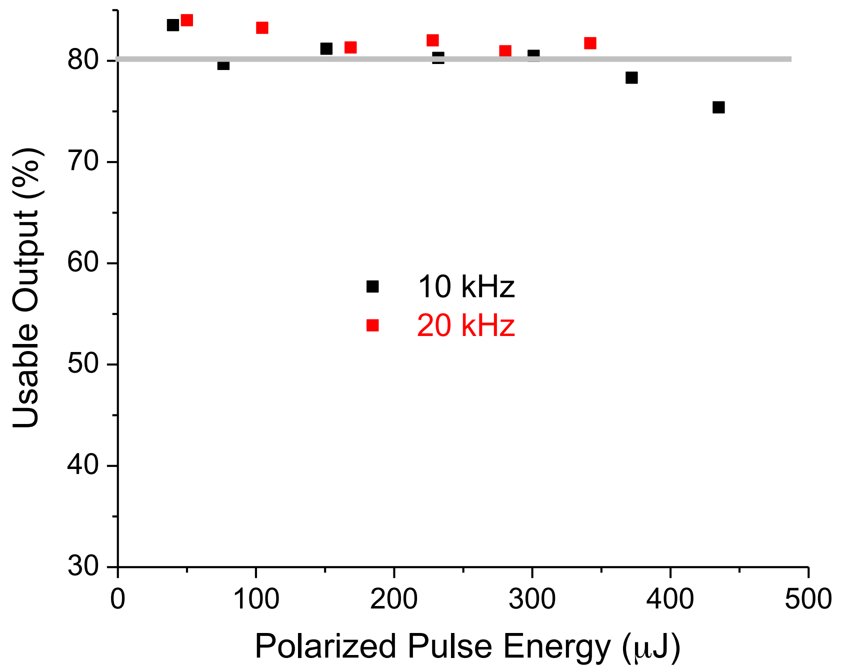
M. Baudelet et al., "Laser induced breakdown spectroscopy of copper with a 2 μm fiber laser," Opt. Ex. **18**, 7905-7910 (2010).

PCF vs Step Index LMA

Step-index fiber with 23 µm MFD, 0.1 NA



PCF with 36 µm MFD, 0.04 NA

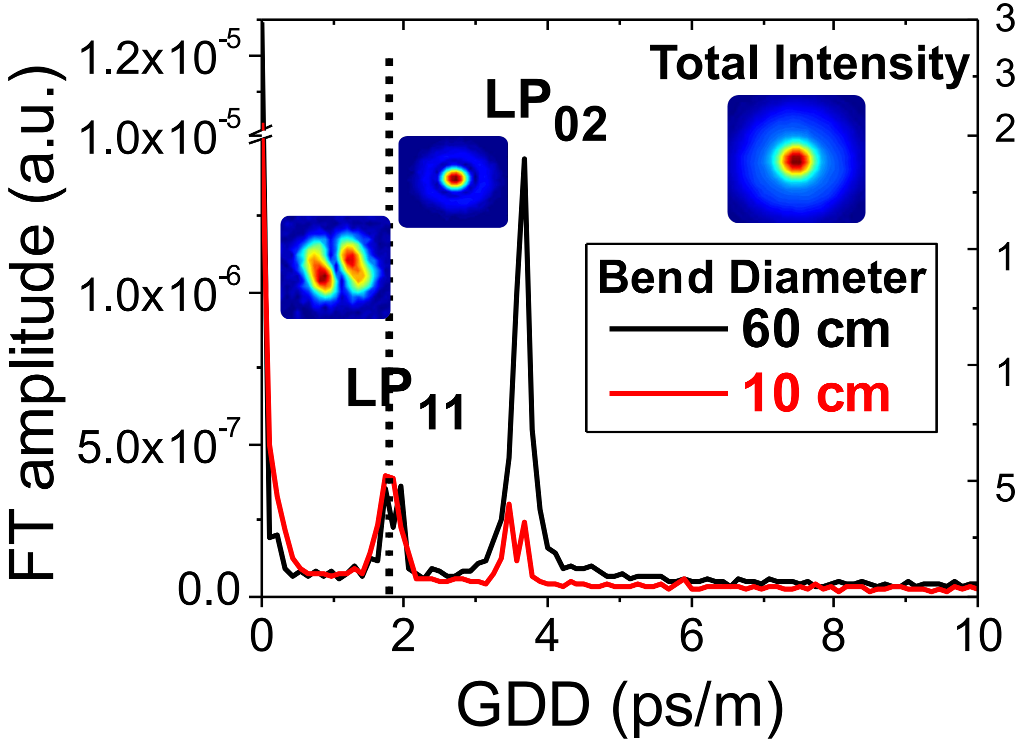


- The percentage of usable output reduces from 80% to <60% starting with pulse energies >100 µJ and a minimum pulse duration of 150 ns
- No such degradation occurs using PCF, enabling energy scaling to 435 µJ energy with 49 ns pulse duration

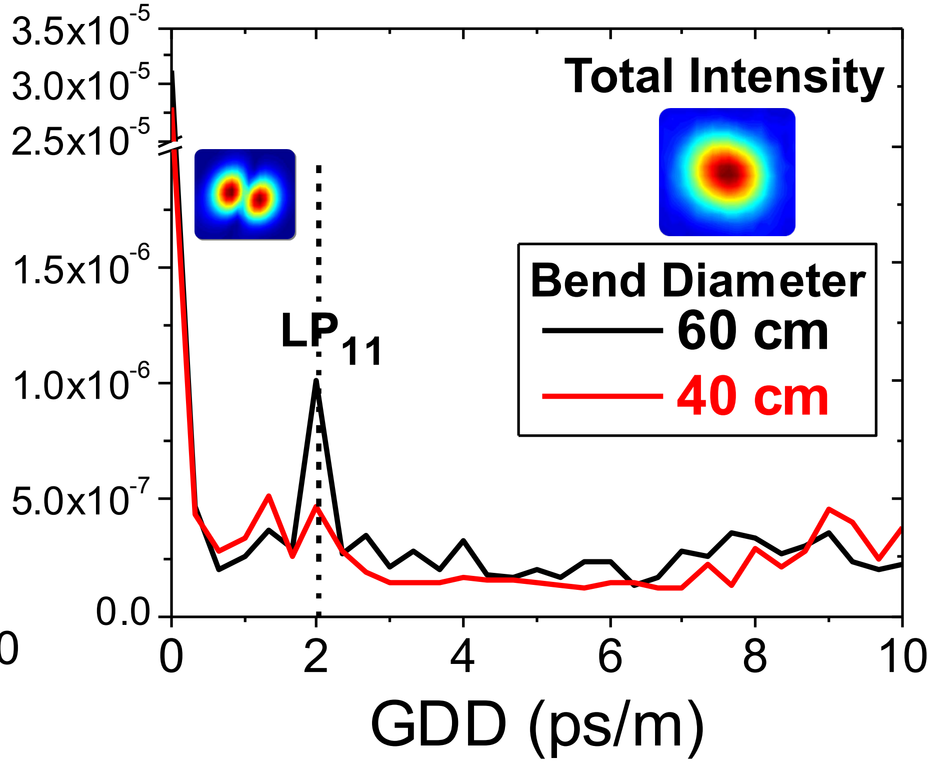
P. Kadwani et al., "Comparison of higher-order mode suppression and Q-switched laser performance in thulium-doped large mode area and photonic crystal fibers", Opt. Exp. **20**, 24295 (2012)

S² Characterization

Step-index fiber with 23 μm MFD, 0.1 NA



PCF with 36 μm MFD, 0.04 NA



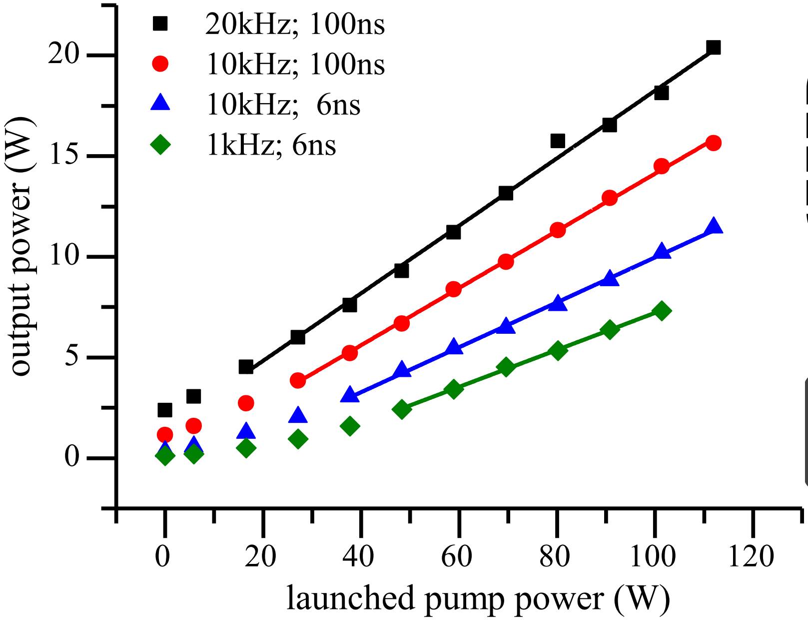
Recent modal characterization measurements confirm Tm-doped PCFs offer significantly larger mode area and reduced higher-order mode content.

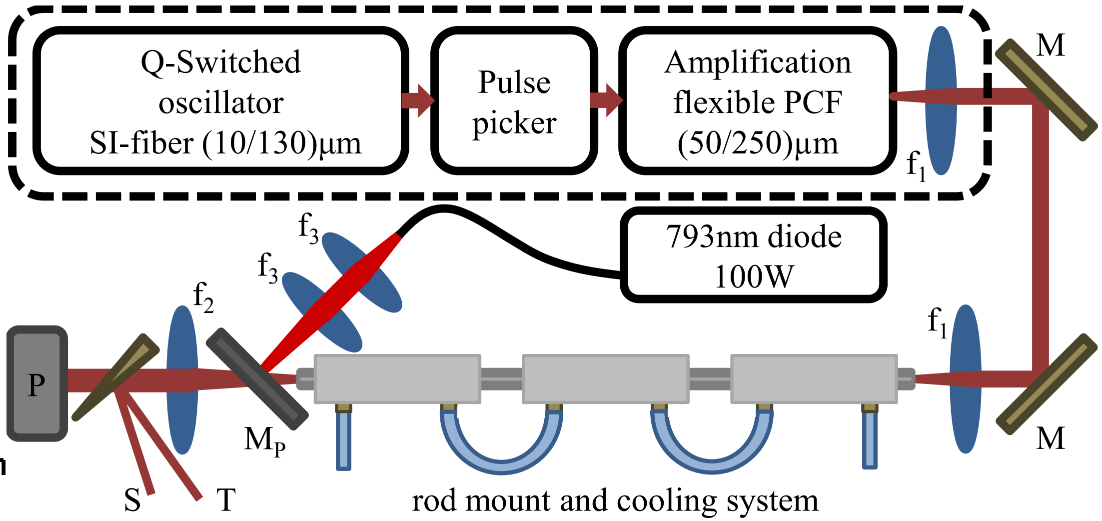
fiber optics lab **This work done with Prof. Axel Schülzgen and Clemence Jollivet**

P. Kadwani et al., "Comparison of higher-order mode suppression and Q-switched laser performance in thulium-doped large mode area and photonic crystal fibers", Opt. Exp. **20**, 24295 (2012)

Nanosecond Peak Power Scaling

Amplification to >890 kW with no evidence of nonlinear pulse degradation





C. Gaida et al., "Amplification of nanosecond pulses to megawatt peak power levels in Tm^{3+}-doped photonic crystal fiber rod", Opt. Lett. **38**, 691 (2013)

>50 W CW in Tm:LPF

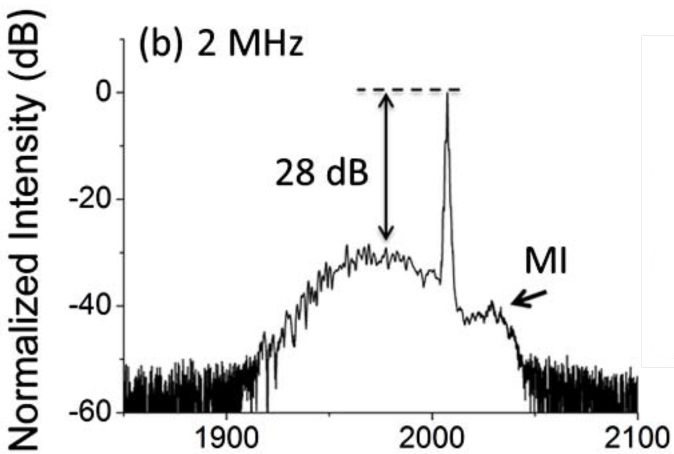
F. Jansen et al., "High-power very large mode-area thulium-doped fiber laser", Opt. Lett. **37**, 4546 (2012)

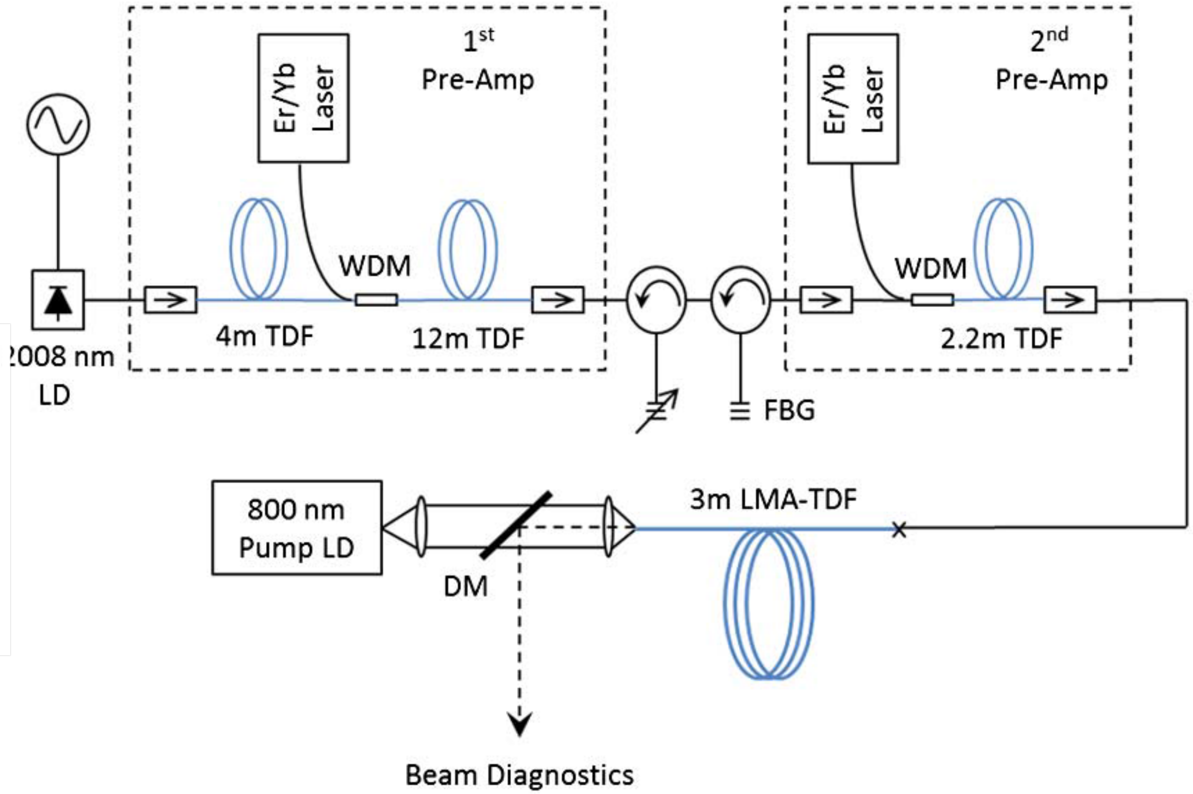
>2.4 mJ, 33 W in Tm:LPF

F. Stutzkiet al., "2.4 mJ, 33 W Q-switched Tm-doped fiber laser with near diffraction-limited beam quality", Opt. Lett. **38**, 97 (2013)

Picosecond

Seed pulses generated by a gain switched InGaAs/InP diode





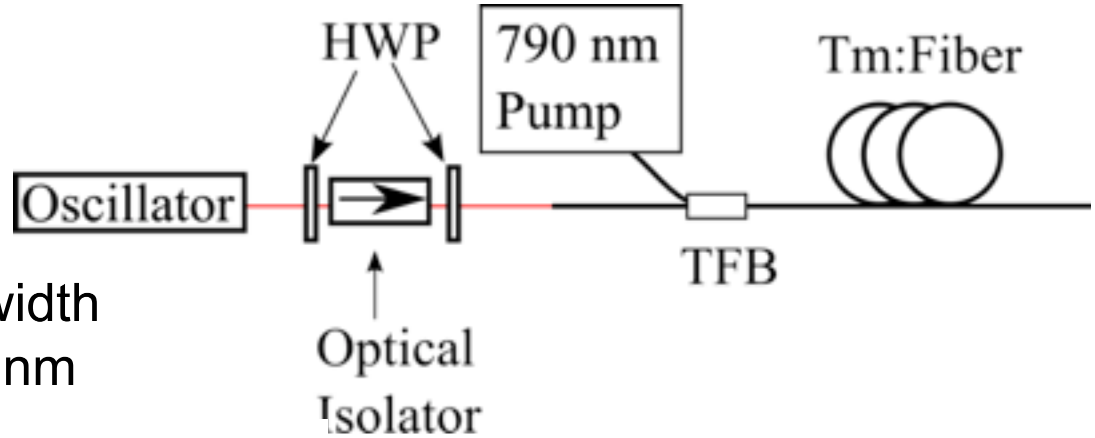
Maximum peak power of 100 kW: 3.5 μJ, 33 ps pulse at 2 MHz

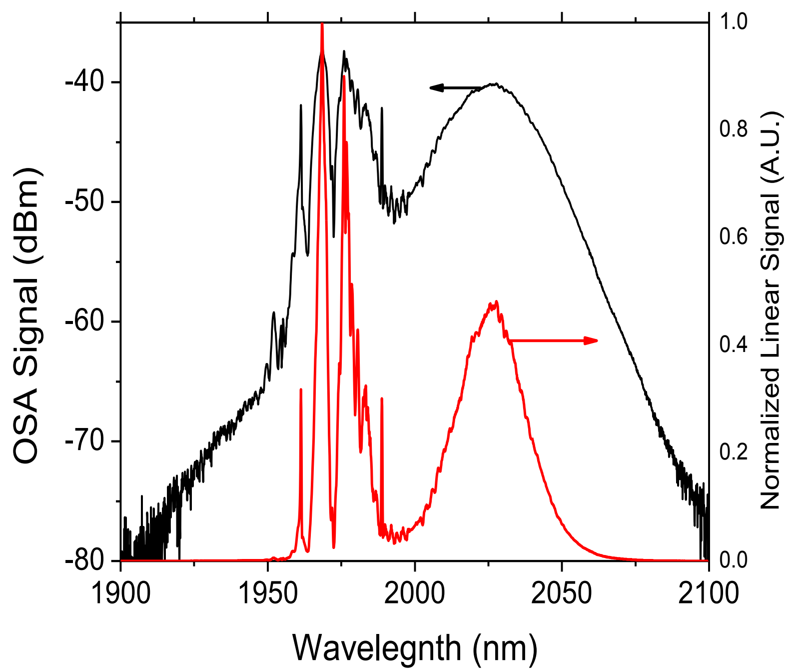
Further scaling claimed to be limited by modal instability (MI)

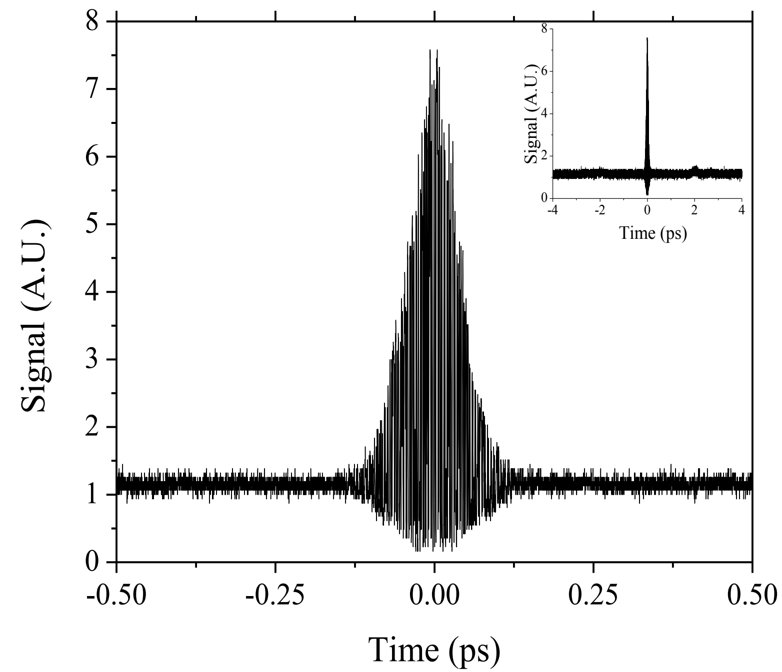
A. M. Heidt et al., “100 kW peak power picosecond thulium doped fiber amplifier system seeded by a gain-switched diode laser at 2 μm”, Opt. Lett. **38**, 1615 (2013)

Femtosecond Front-end

After spectral filtering:
- 3 nJ pulse energy
- ~150 fs pulse duration
- ~30 nm (FWHM) spectral width
- Tuning range 1980 – 2100 nm





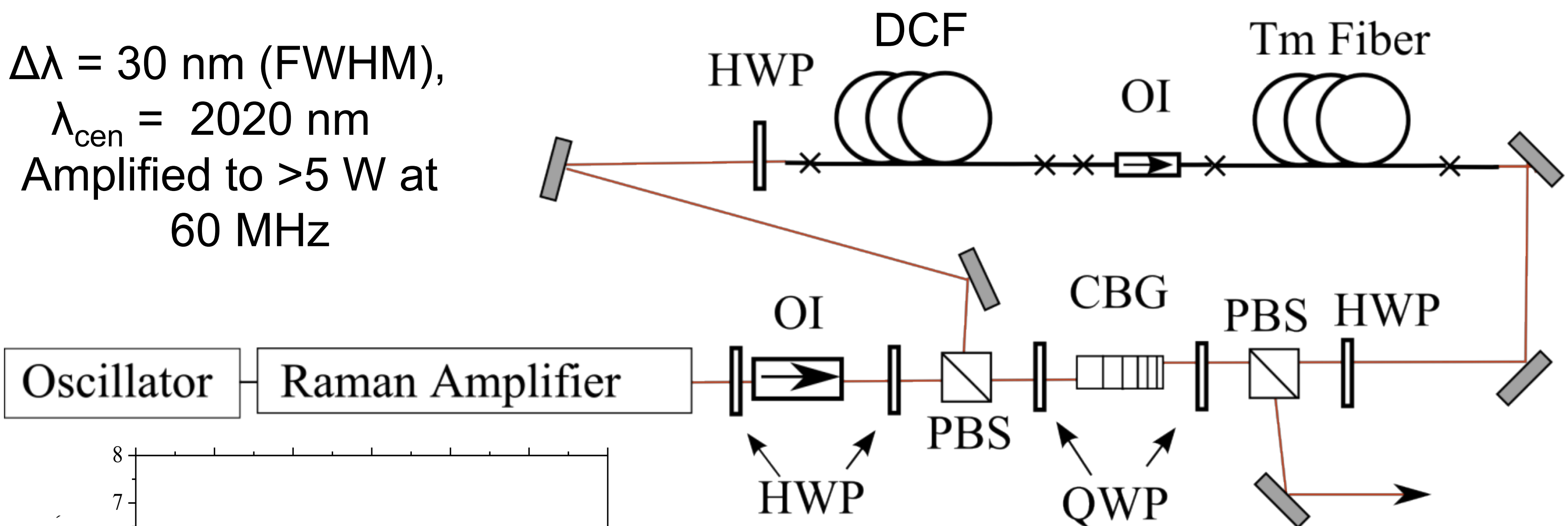


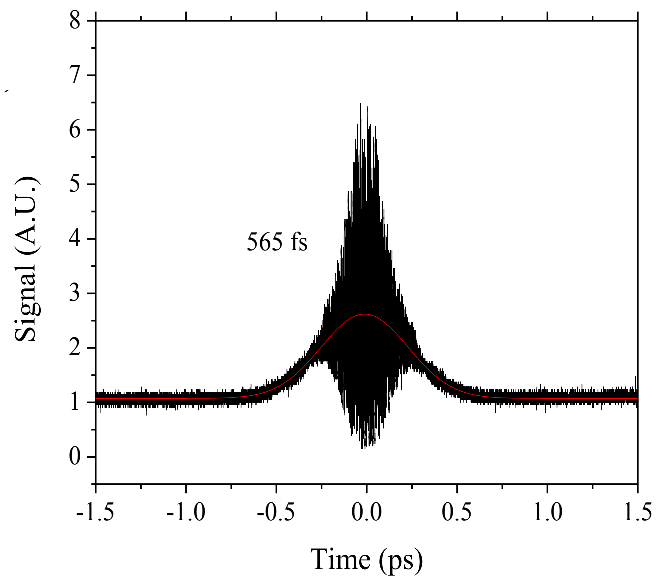
G. Imeshev and M. Fermann, "230-kW peak power femtosecond pulses from a high power tunable source based on amplification in Tm-doped fiber", Opt. Ex. **13**, 7424 (2005)

Tm:fiber CPA with CBG

Pulse stretching to 160 ps and recompression
using a Chirped Bragg Grating (CBG) from OptiGrate

$\Delta\lambda$ = 30 nm (FWHM),
λ_{cen} = 2020 nm
Amplified to >5 W at 60 MHz





A. Sims et al., "Chirped pulse amplification in single mode Tm:fiber using a chirped Bragg grating", App. Phys. B.(2013)

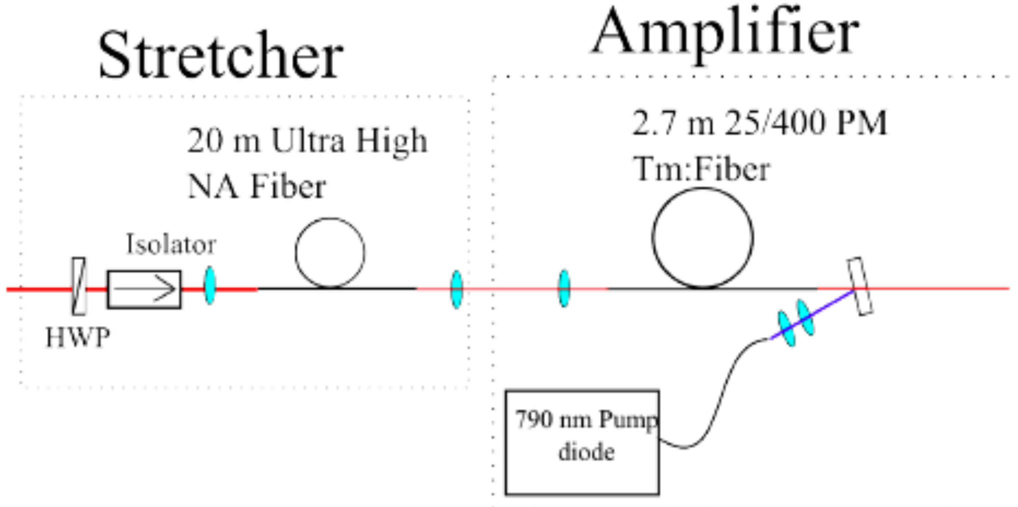
A. Sims et al., "1 μJ, sub-500 fs chirped pulse amplification in a Tm-doped fiber system", Opt. Lett.**38**,121 (2013)

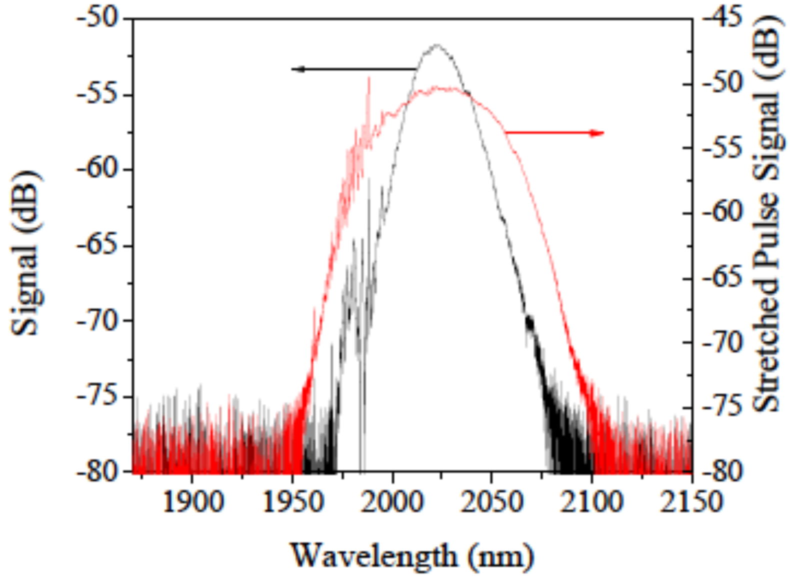
37 μJ in 910 fs

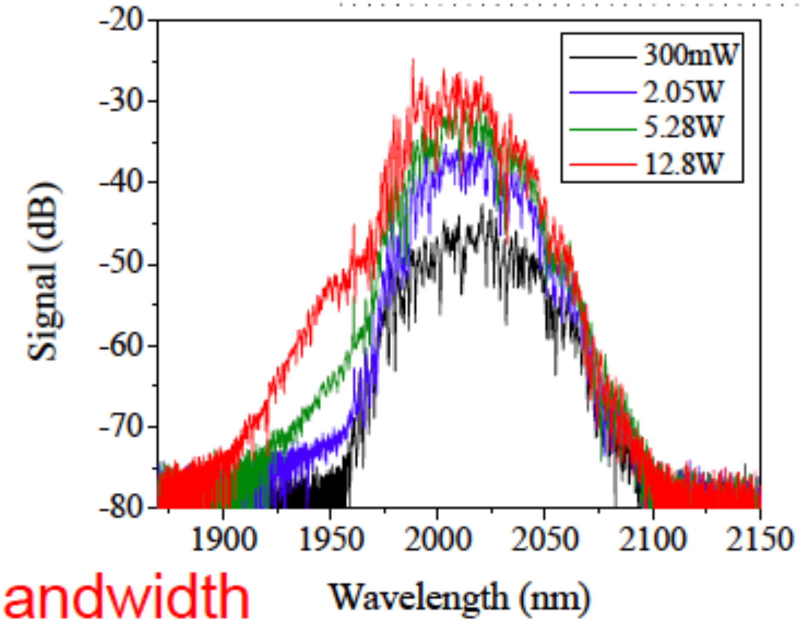
P. Wan et al., "High pulse energy 2 μm femtosecond fiber laser", Opt. Ex.**21**,1798 (2013)

Utilizing the Bandwidth

Normal GVD stretcher fiber
Pulse duration ~40 ps
Similarton-like pulse broadening
from 29 to 60 nm







Center Wavelength 2020 nm
Average Power 12.8 W
182 nJ uncompressed, 60 nm Bandwidth

Pulsed Summary

- In the last two years, the development of CPA systems has accelerated greatly - >MW peak power, <100 fs
- Nanosecond system development is maturing - MW peak power, 1-10 ns range
- Picosecond laser development has lagged behind CPA and nanosecond, but is rapidly emerging 100 kW peak power, ~30 ps

Outline

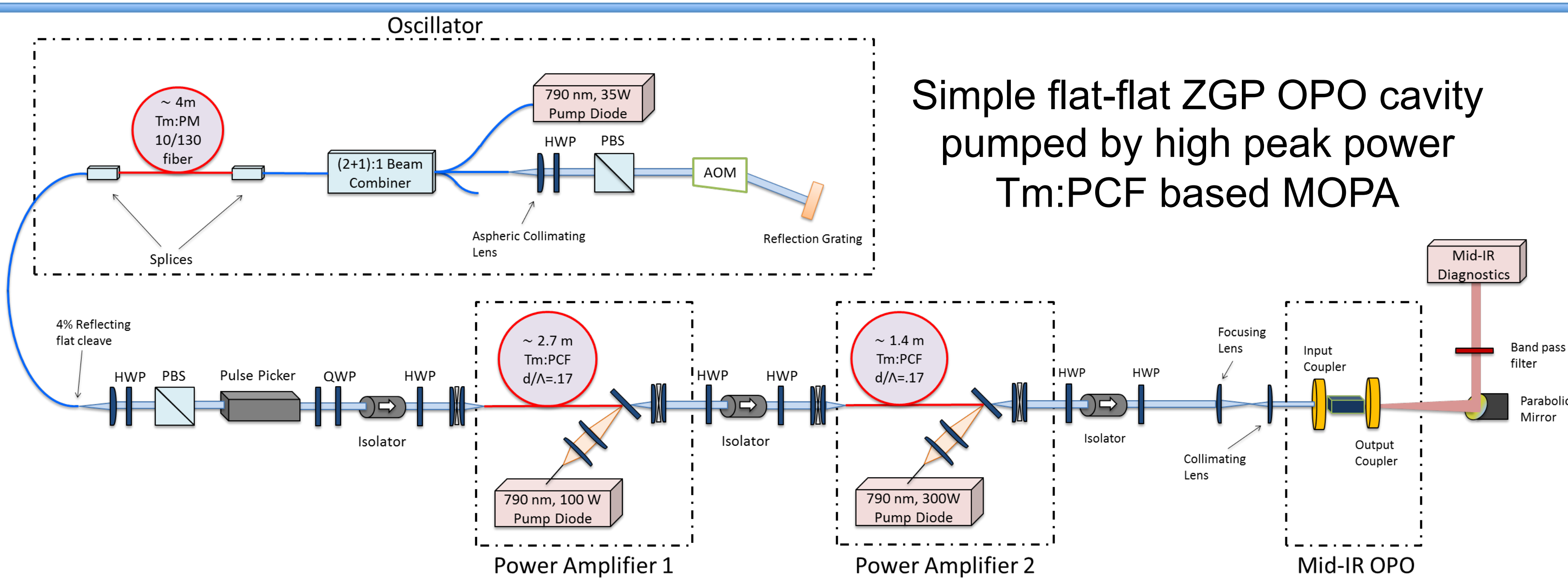
- Review of 2 μm fiber laser development
  - CW
  - Pulsed
- Application
  - Nonlinear pump

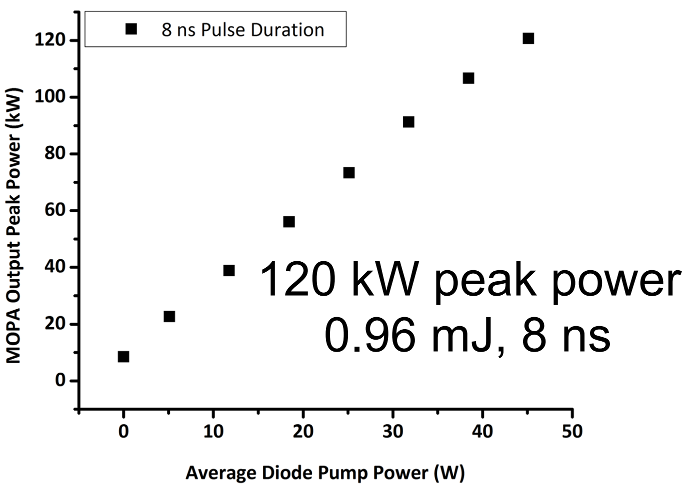
Another entire area of application for 2 μm fiber laser is in telecommunication, using HC-PBF

Z. Li et al., "Thulium-doped fiber amplifier for optical communications at 2 μm", Opt. Ex. **13**, 7424 (2005)

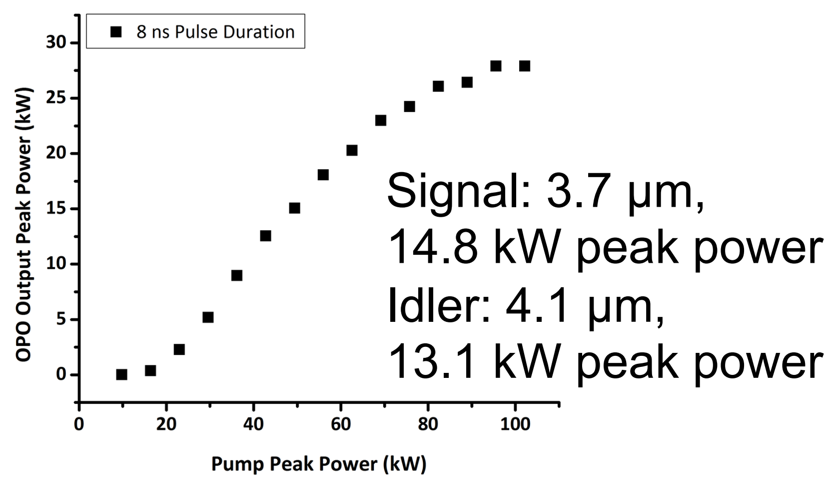
Nanosecond OPO

Simple flat-flat ZGP OPO cavity pumped by high peak power Tm:PCF based MOPA

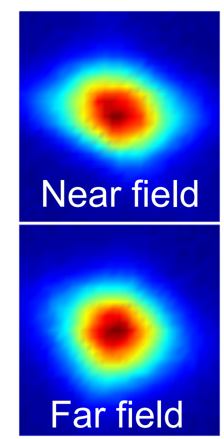




120 kW peak power
0.96 mJ, 8 ns



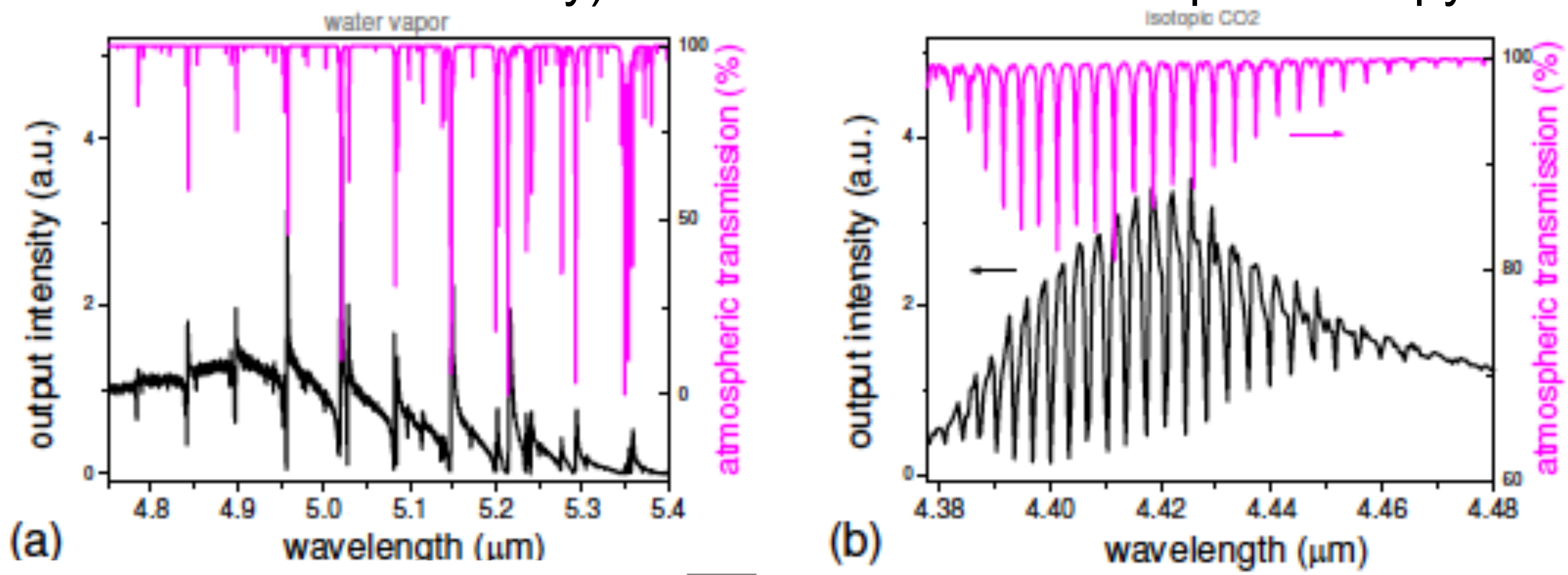
Signal: 3.7 µm,
14.8 kW peak power
Idler: 4.1 µm,
13.1 kW peak power

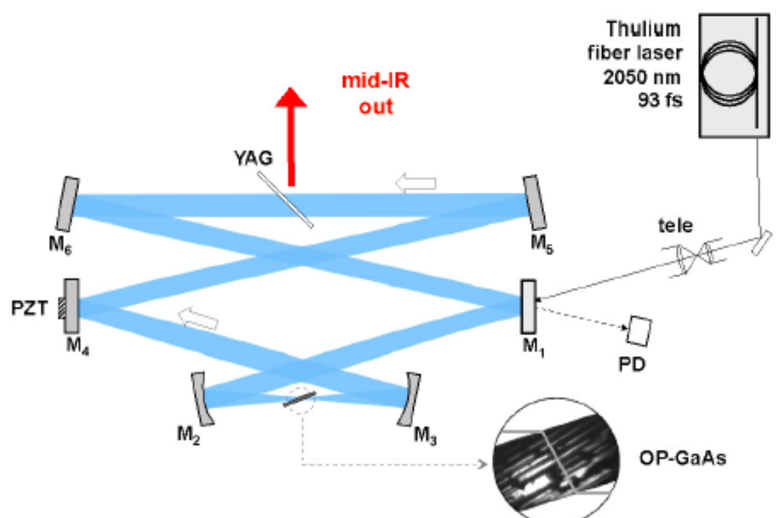


D. Creeden et al., “Mid-infrared $ZnGeP_2$ parametric oscillator directly pumped by a pulsed 2 µm Tm-doped fiber laser”, Opt. Lett. **33**, 315 (2008)

Mid-IR Frequency Combs

The combination of Tm:fiber frequency comb and nonlinear conversion (OPO enhancement cavity) offers new tools mid-IR spectroscopy

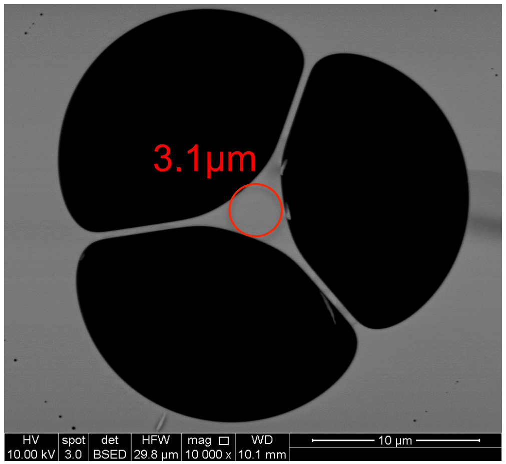


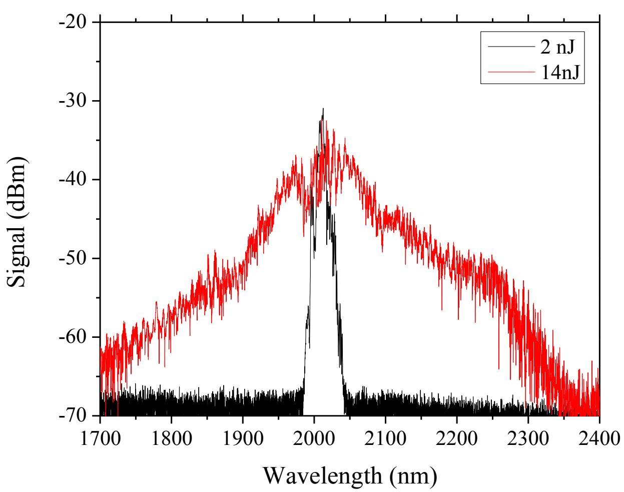


N. Leindecker et al., "Octave-spanning ultrafast OPO with 2.6-6.1 μm instantaneous bandwidth pumped by femtosecond Tm-fiber laser", Opt. Ex.**20**,7046 (2012)

Supercontinuum Generation

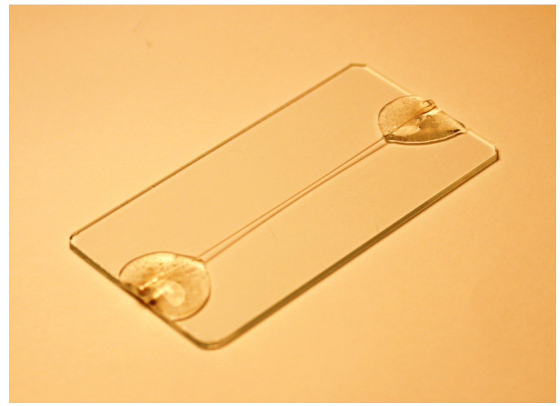
In tellurite fiber





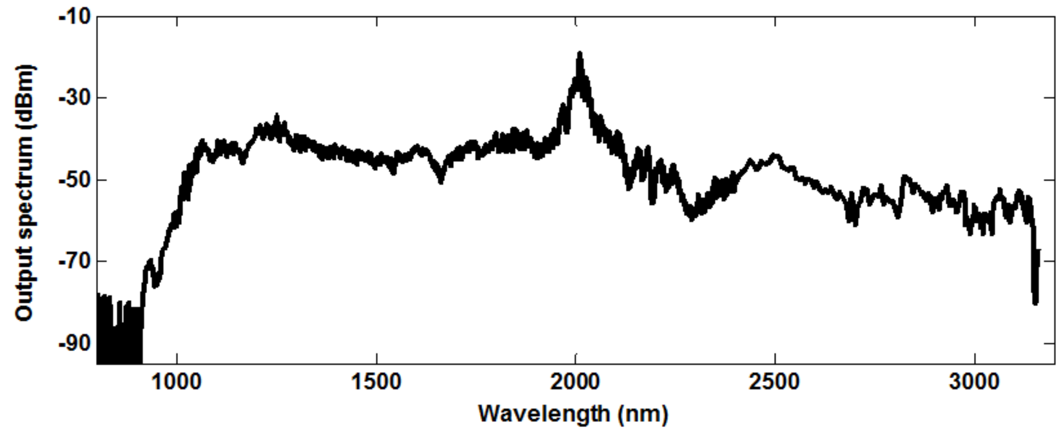
This fiber supplied by Profs. Heike Ebendorff-Heidepriem and Tanya Monro, Univ. of Adelaide

In chalcogenide fiber



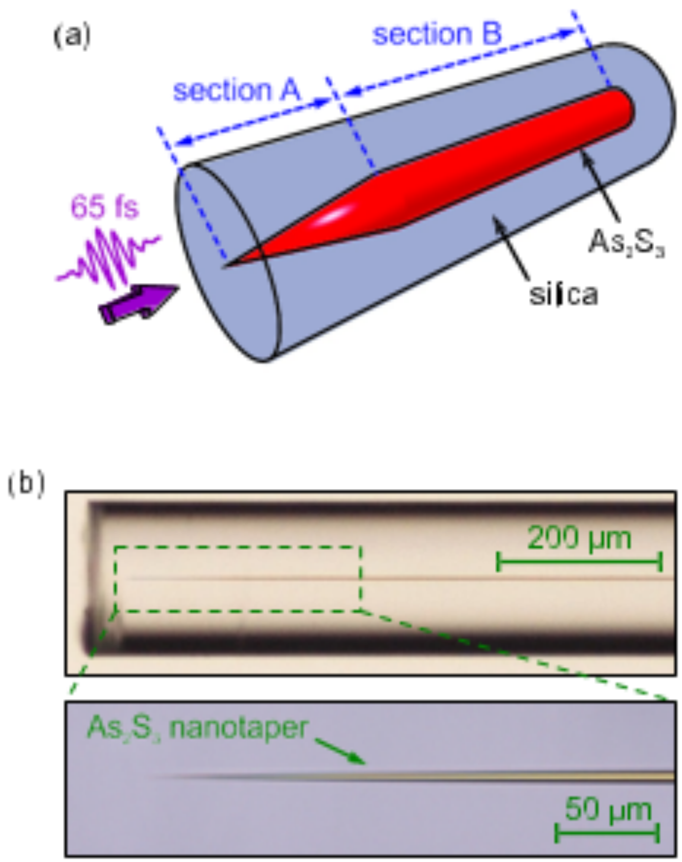
Laser:
- Pulse duration: 450 fs
- Peak power: 9.6 kW

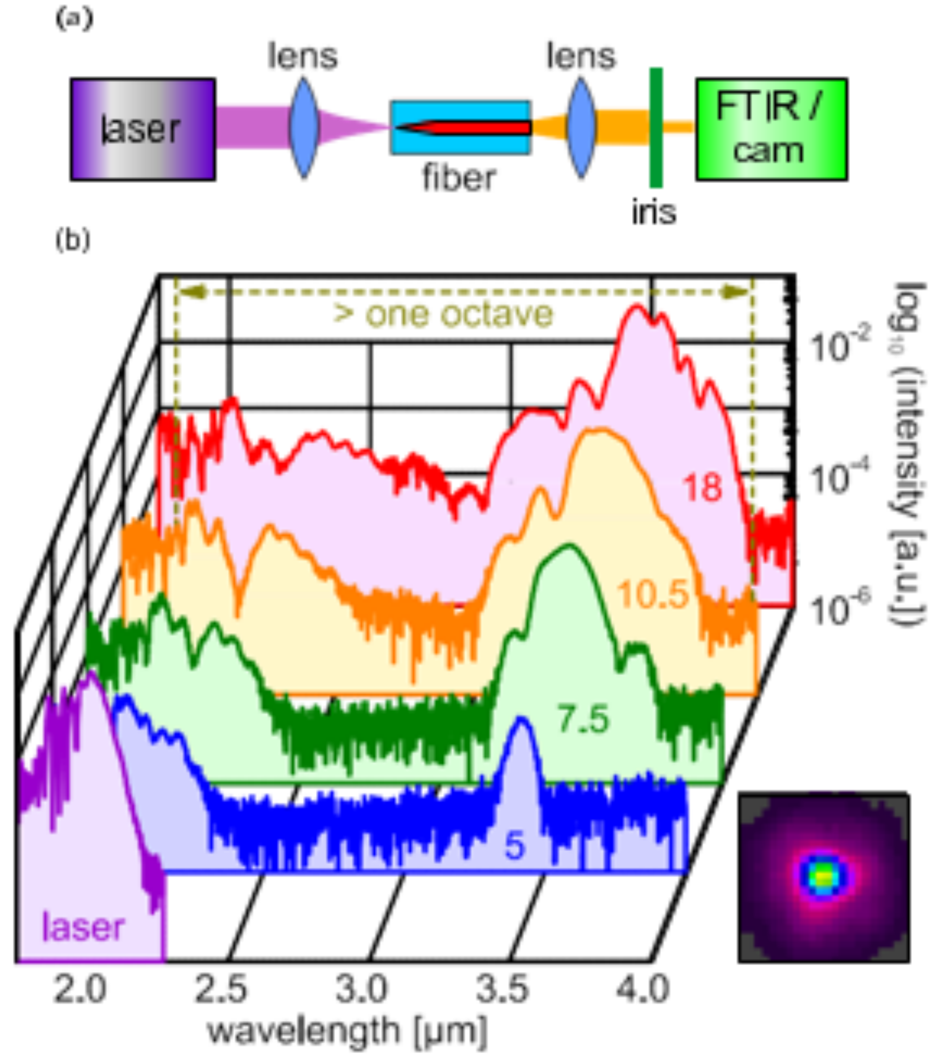
Sample:
- Length: 6.8cm
- Minimum core: 250 nm
- Core: $As_2Se_{1.5}S_{1.5}$
- Cladding: As_2S_3



This work done in collaboration with Prof. Ayman Abouraddy and Soroush Shabahang

Supercontinuum Generation





N. Granzow et al., "Mid-IR supercontinuum generation in As_2S_3-silica "nano-spike" step-index waveguide", Opt. Ex. **21**, 10970 (2013)

Nonlinear Pump Summary

- 2 μm fiber lasers have proven a unique source for pumping nonlinear processes particularly the generation of mid-IR
- Excellent beam quality and high average power are readily achievable
- Additional processes will be enabled by the continued advance in Tm: and Ho: fiber sources

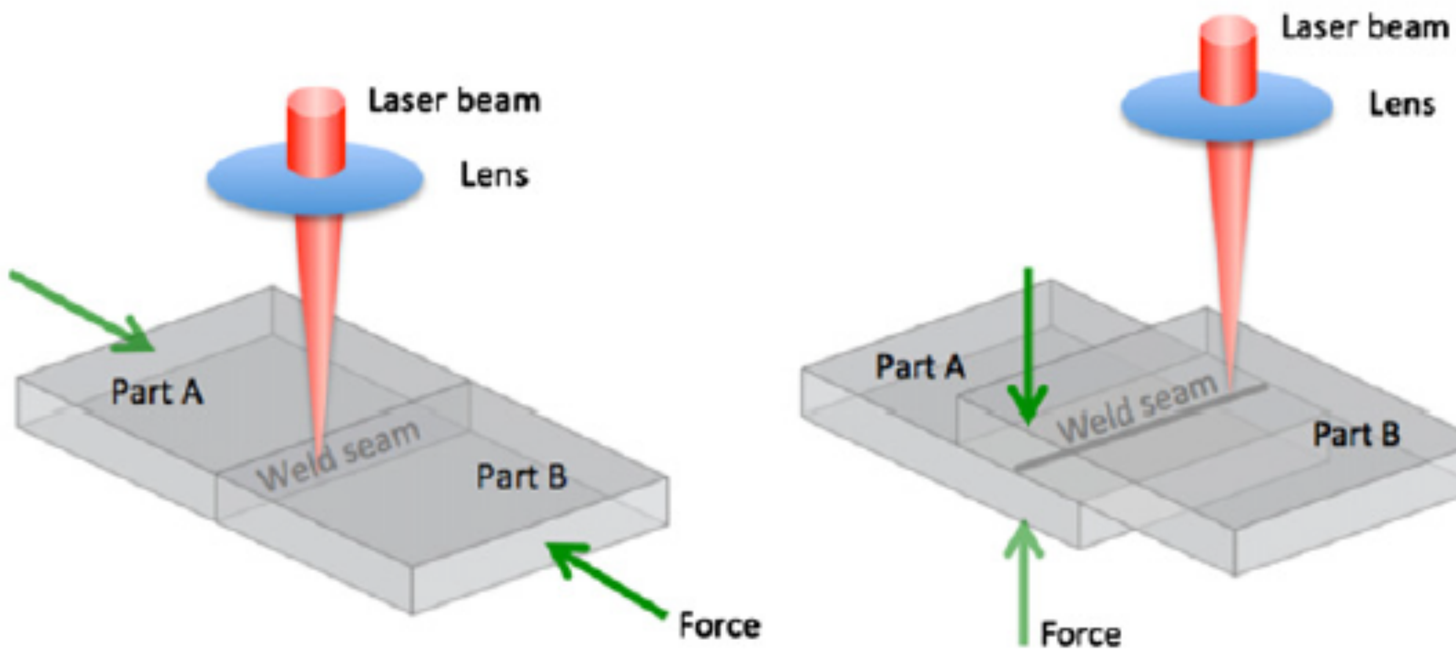
Final Questions

- CW – How to improve dopant material to achieve high efficiency?
- Pulsed – Can 2 μm fiber lasers take advantage of lower nonlinearity to exceed Yb:fiber lasers in peak power?
- Nonlinear pump – Can 2 μm fiber lasers compete with the peak power from Ho:solid-state systems?

Thank You!

Materials Processing

The 2 μm wavelength is attractive
for polymer welding

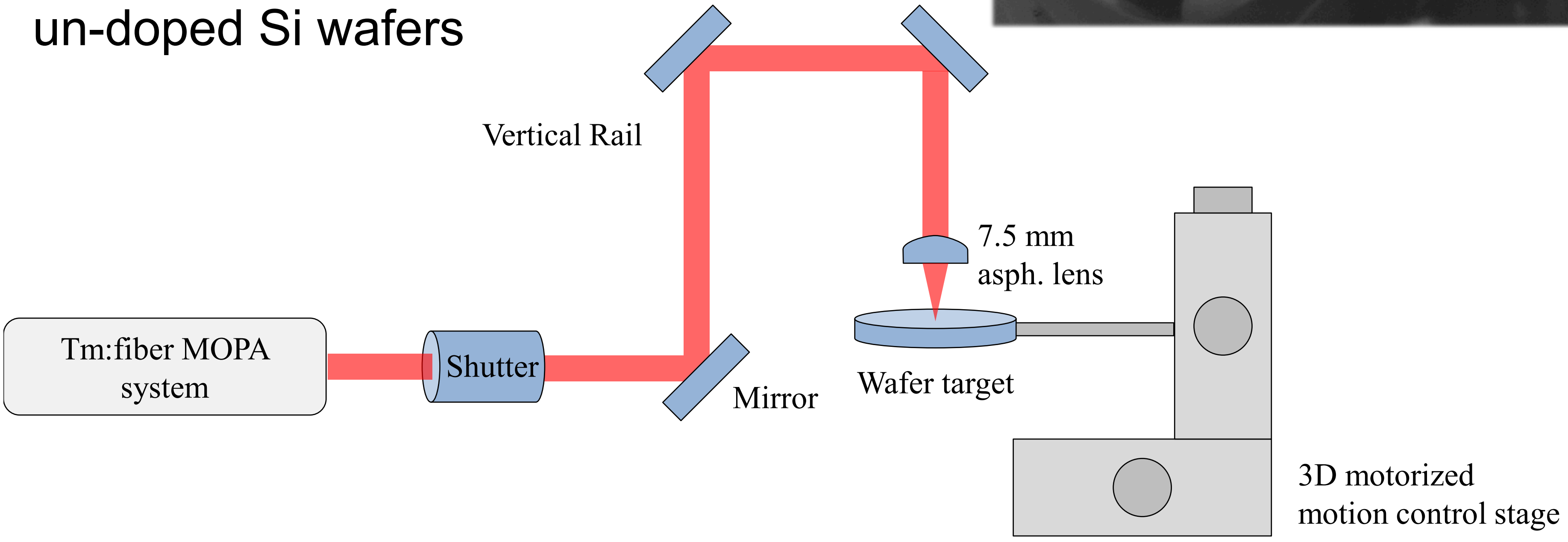


I. Mingareev et al., "Welding of polymers using a 2 μm fiber laser," Opt. and Laser Tech. **44**, 2095 (2012)

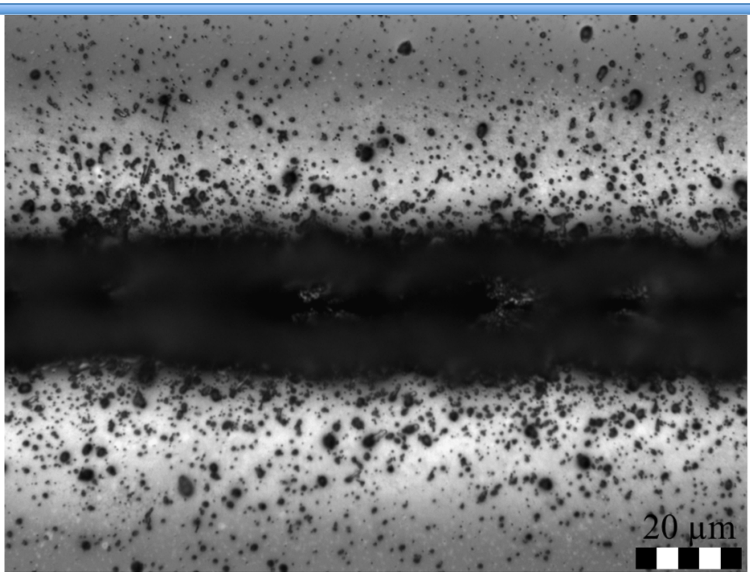
Si “Backside” Machining

On target:
Maximum energy E = 200 μJ
Minimum diameter d = 10 μm
Maximum fluence F = 255 J/cm^2

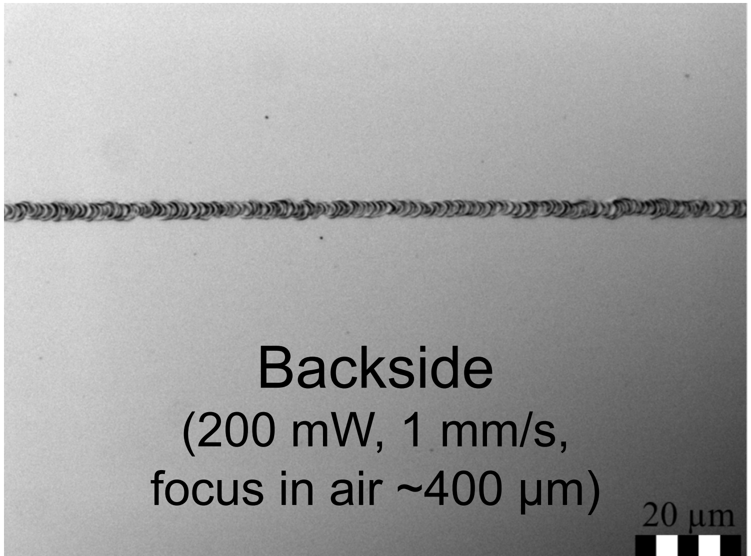
Target:
500 μm thick, DSP
un-doped Si wafers



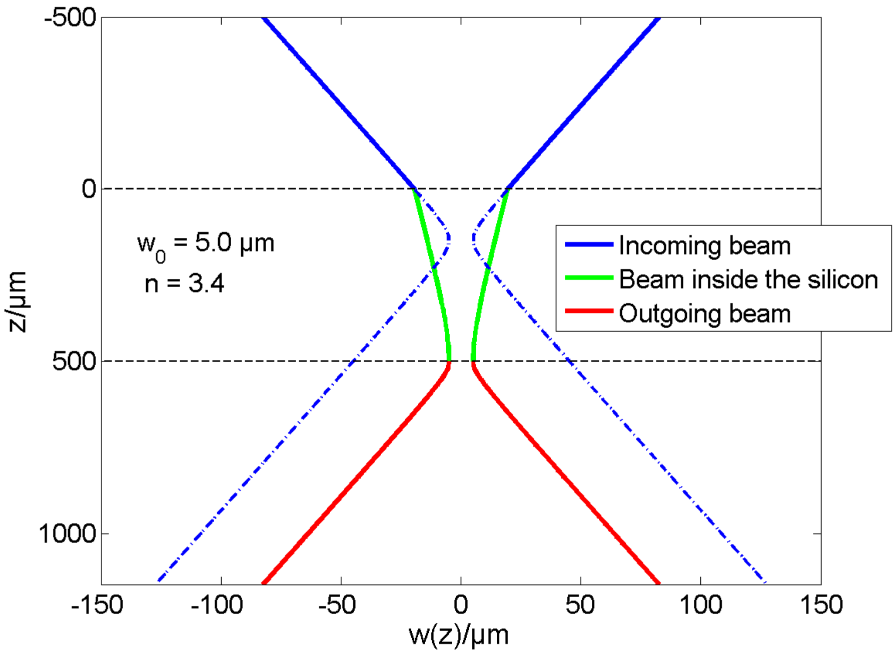
Si "Backside" Machining



Front
(200 mW, 1 mm/s, focus 0 μm)



Backside
(200 mW, 1 mm/s,
focus in air ~400 μm)



Front and backside machining look very different, and require very different powers!