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Overview of Optical Fiber and Fiber Laser R&D at Lawrence Livermore Laboratory

September 9, 2014

Jay W. Dawson, Mike Messerly, Matt Prantil, Reggie Drachenberg, Graham Allen, Paul Pax, John Heebner

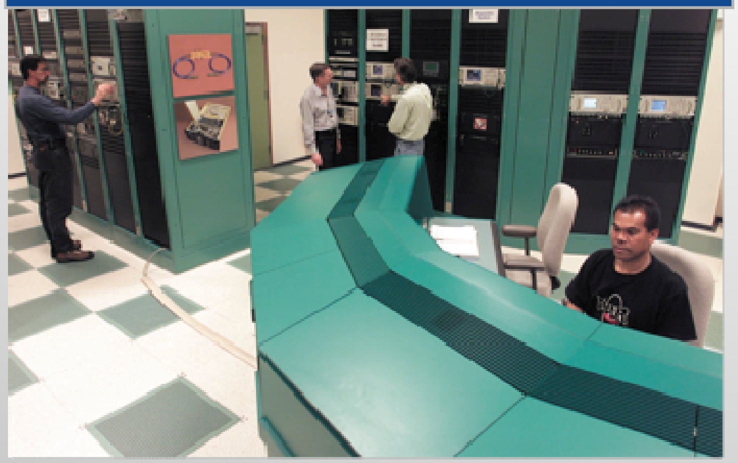
Lawrence Livermore National Laboratory

LLNL-PRES-610652

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Fiber-based injection seed lasers are an ongoing LLNL need

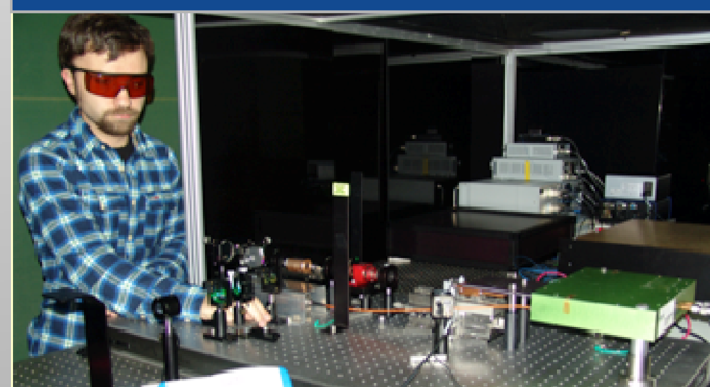
NIF & ARC MOR



Mercury Injection Seed Laser

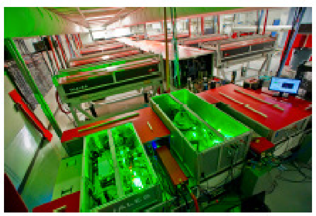
T-REX PDL and Interaction Seed

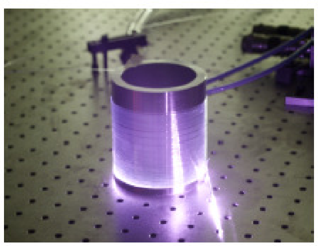
LBNL Photo-Cathode Drive



A future interest is laser technology for accelerator applications

U.S. DEPARTMENT OF ENERGY





Workshop on Laser Technology for Accelerators

Summary Report

January 23–25, 2013

International Coherent Amplifier Network (ICAN)

The future is fibre accelerators

Gerard Mourou, Bill Brocklesby, Toshiki Tajima and Jens Limpert

Could massive arrays of thousands of fibre lasers be the driving force behind next-generation particle accelerators? The International Coherent Amplification Network project believes so and is currently performing a feasibility study.

The challenge of producing the next generation of particle accelerators, for both fundamental research at laboratories such as CERN and more applied tasks such as proton therapy and nuclear transmutation, has been taken up by the high-intensity laser community. With the advent of chirped pulse amplification (CPA) in 1985[1] came the ability to generate ultrashort laser pulses with intensities in excess of 10^{18} W cm^{-2}. At these intensities, the electromagnetic field drives electrons into relativistic motion, opening the door to useful effects like wakefield acceleration[2] and hard X-ray production by bremsstrahlung, Compton or betatron emission[3]. Ion motion becomes relativistic[4] at intensities above 10^{22} W cm^{-2} — an intensity regime demonstrated or anticipated with development projects for very-large-scale

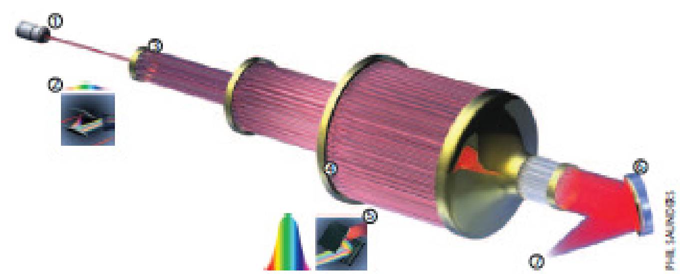
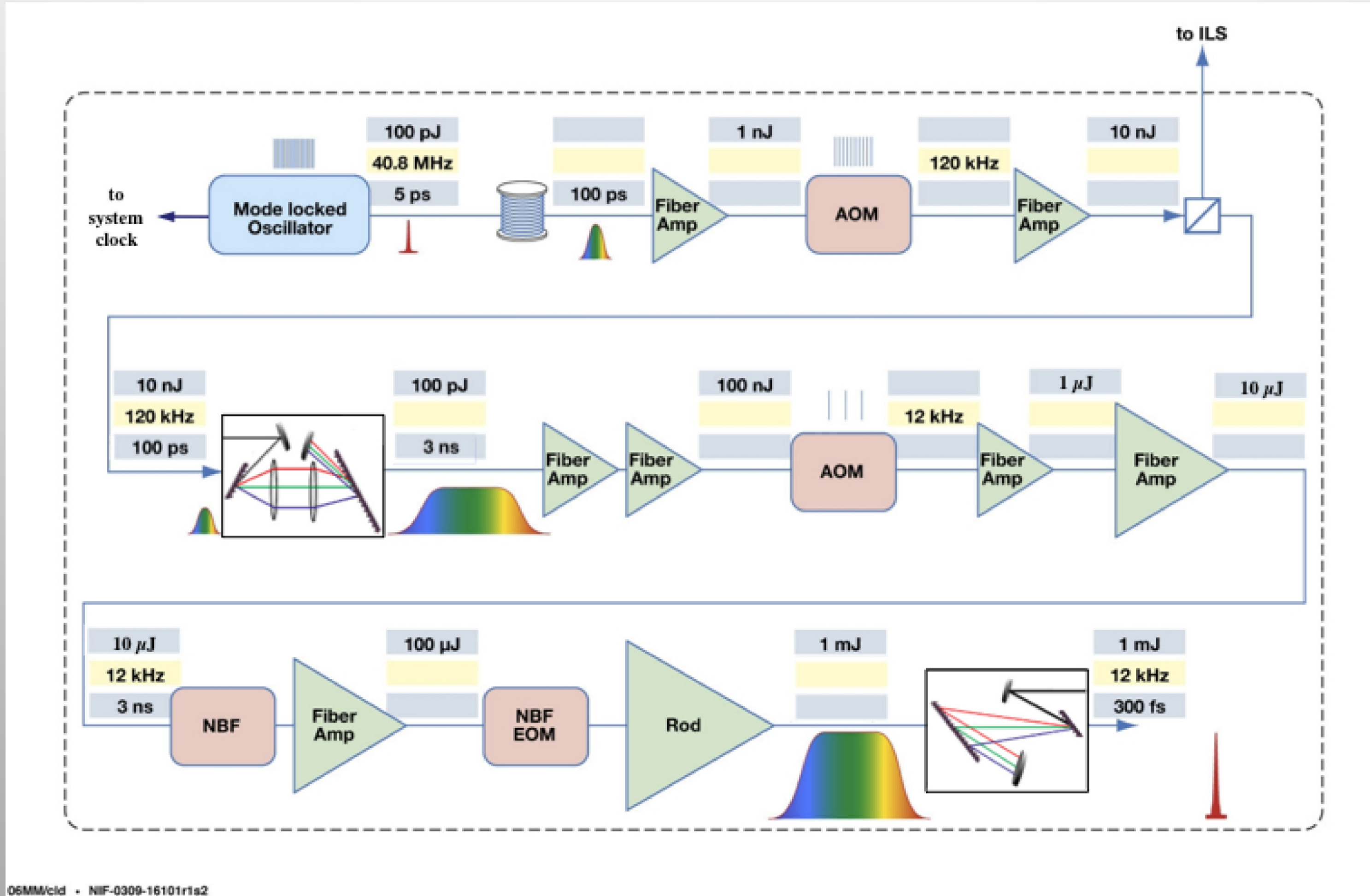


Figure 1 | Principle of a coherent amplifier network. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of ~10 kHz (7).

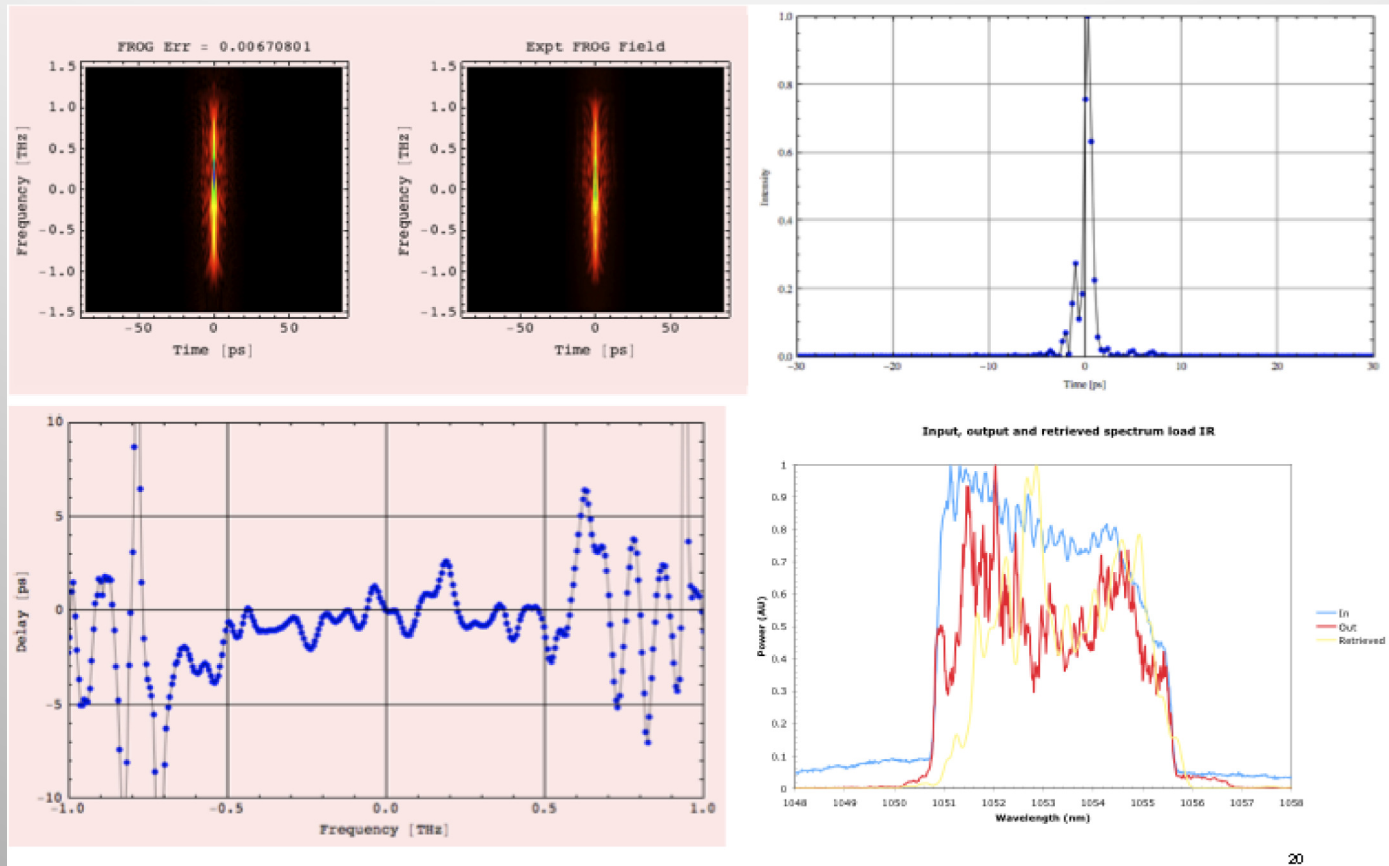
G. Mourou, B. Brocklesby, T. Tajima, J. Limpert, Nature Photonics vol. 7, pp. 258 (2013)

http://science.energy.gov/%7E/media/hep/pdf/accelerator-rd-stewardship/Lasers_for_Accelerators_Report_Final.pdf

Block diagram of a single arm short pulse fiber laser system

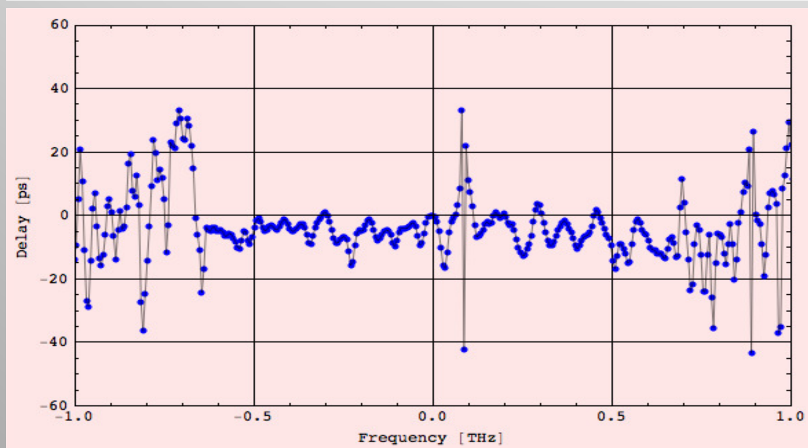


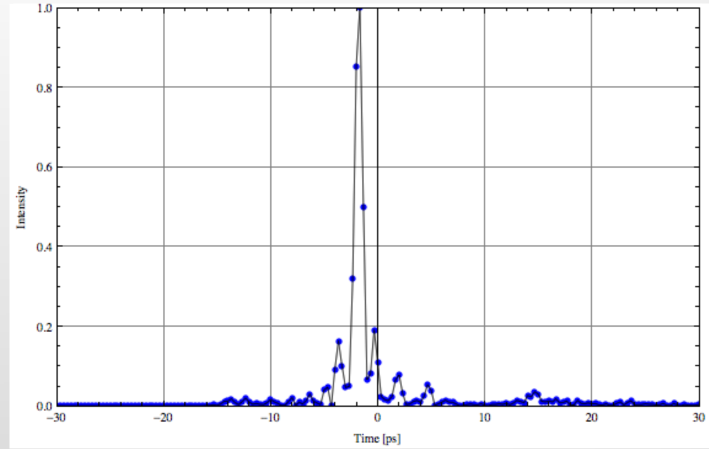
Pulse quality in short pulse fiber laser is a significant challenge

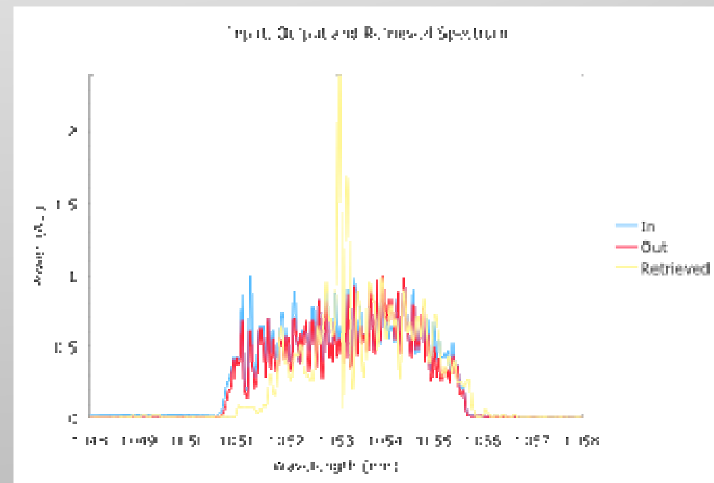


FROG data from a system producing 1μJ pulses

The challenge increases with higher pulse energy

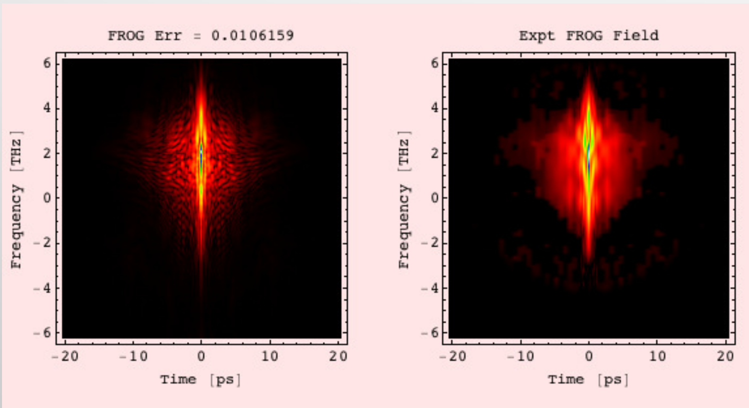


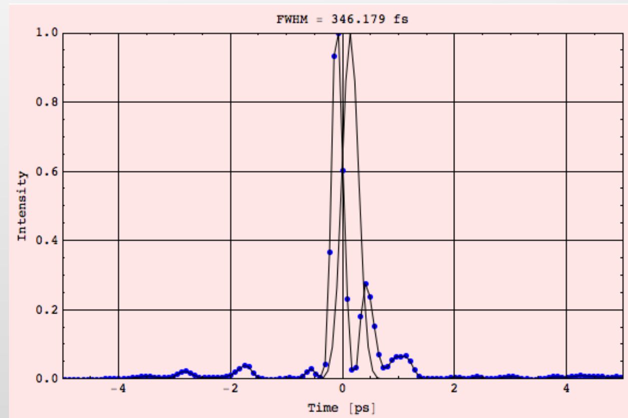


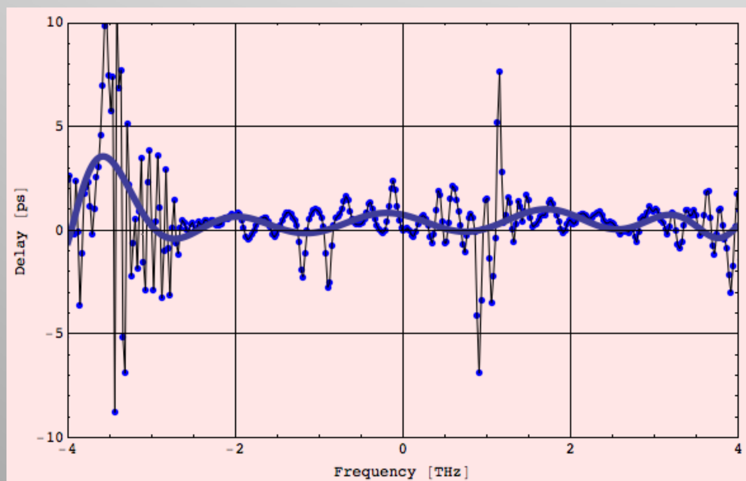


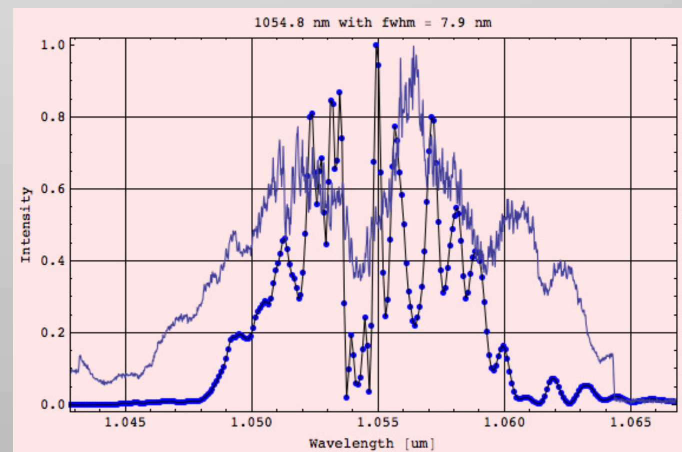
FROG data from a system producing 100 µJ pulses B = 6, Chirped Fiber Bragg Grating Stretcher

Lowering B and using a bulk stretcher improves the pulse



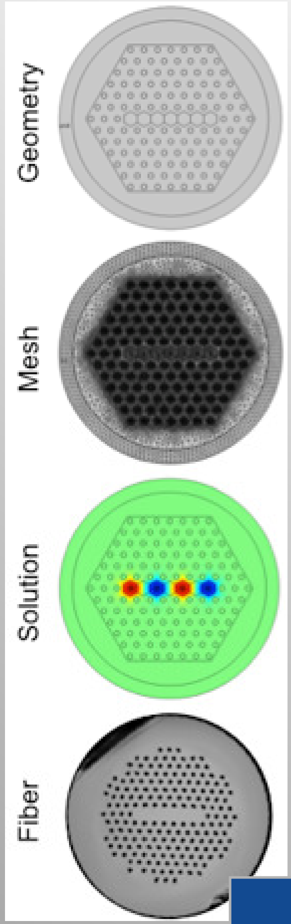




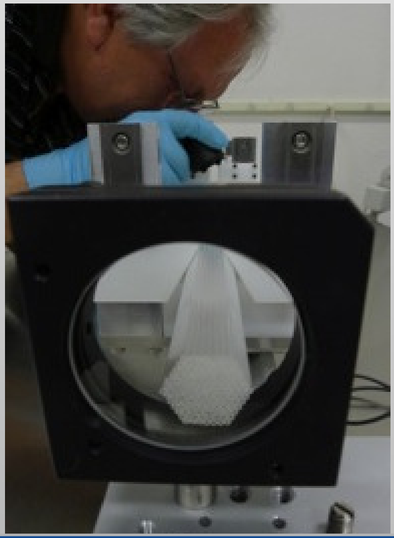


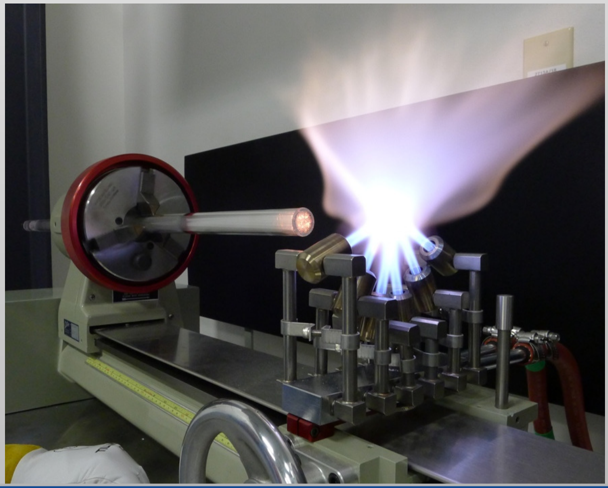
FROG data from a system producing 500µJ pulses

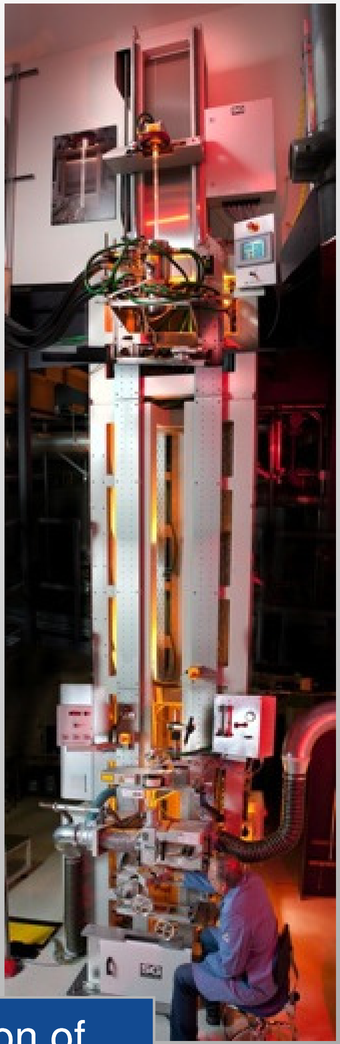
In FY12, we commissioned optical fiber fabrication at LLNL



- Computational design expertise
- “Stack and draw” photonic crystal fiber preforms
- 8.2 m optical fiber draw tower

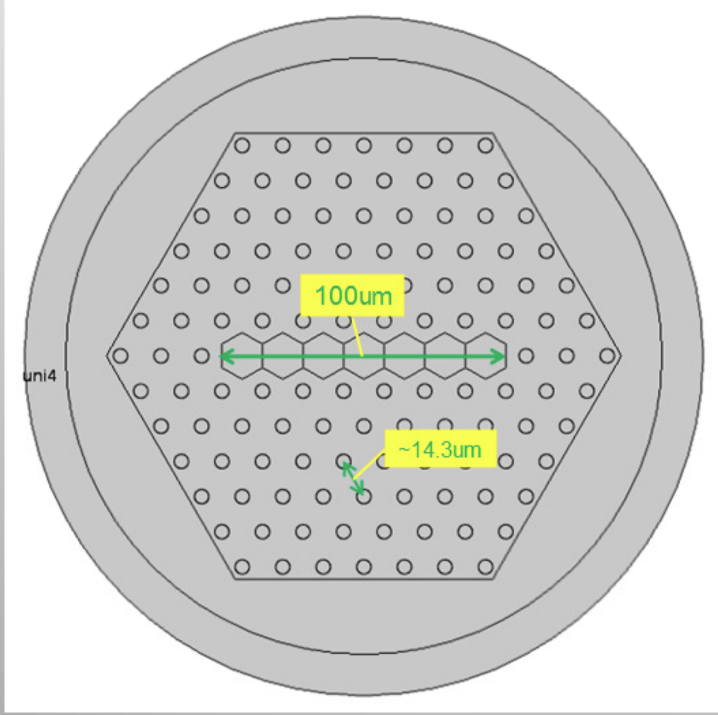


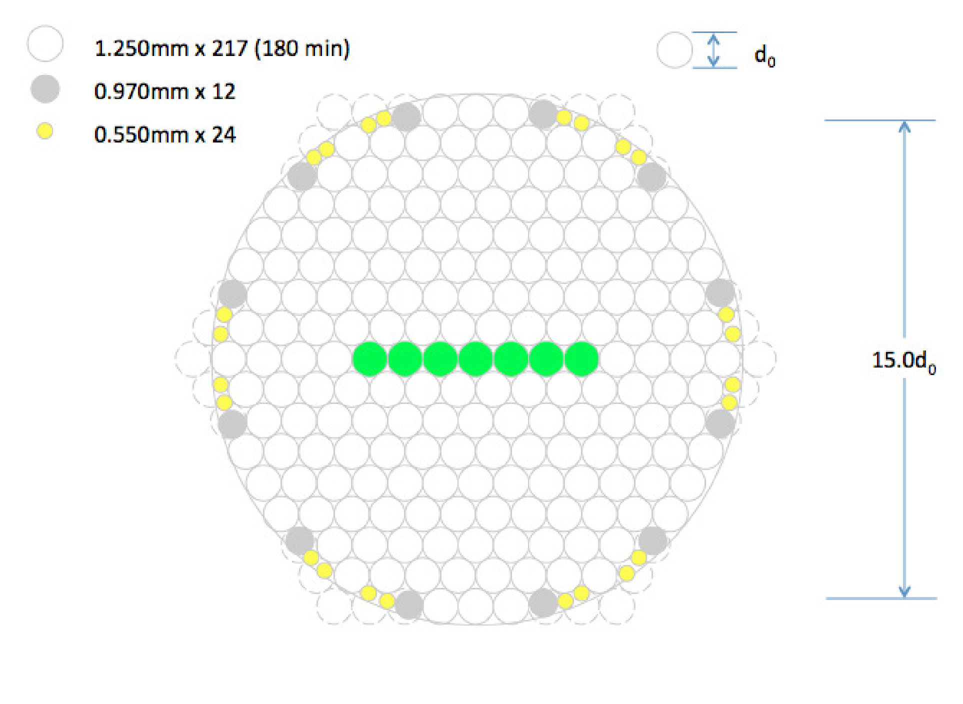




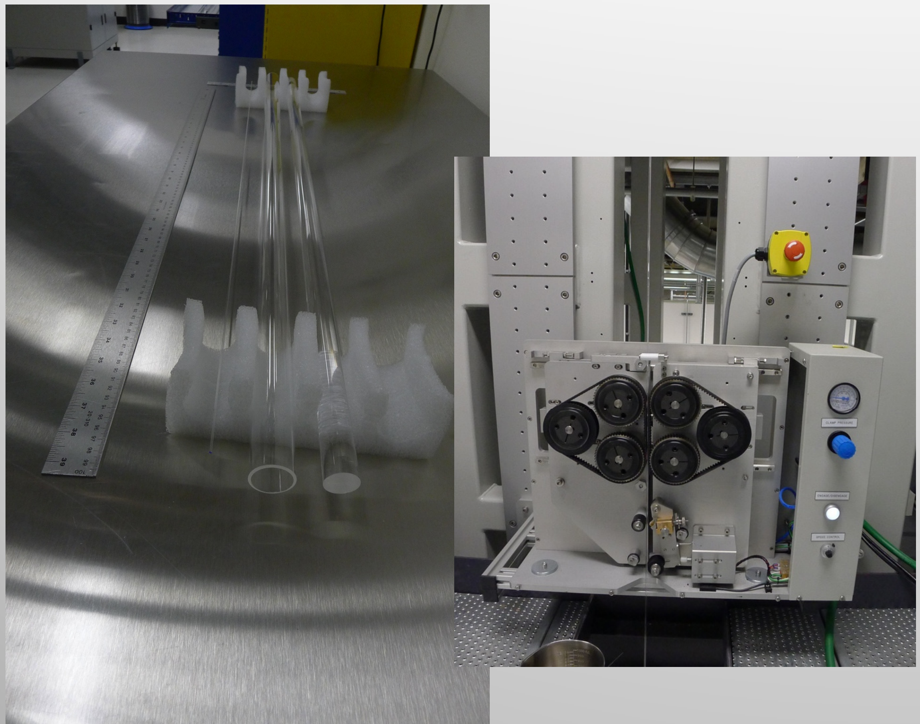
Only facility in the DOE complex and unique for co-location of process development and advanced computing power.

Fibers are designed and then a manufacturing plan is created

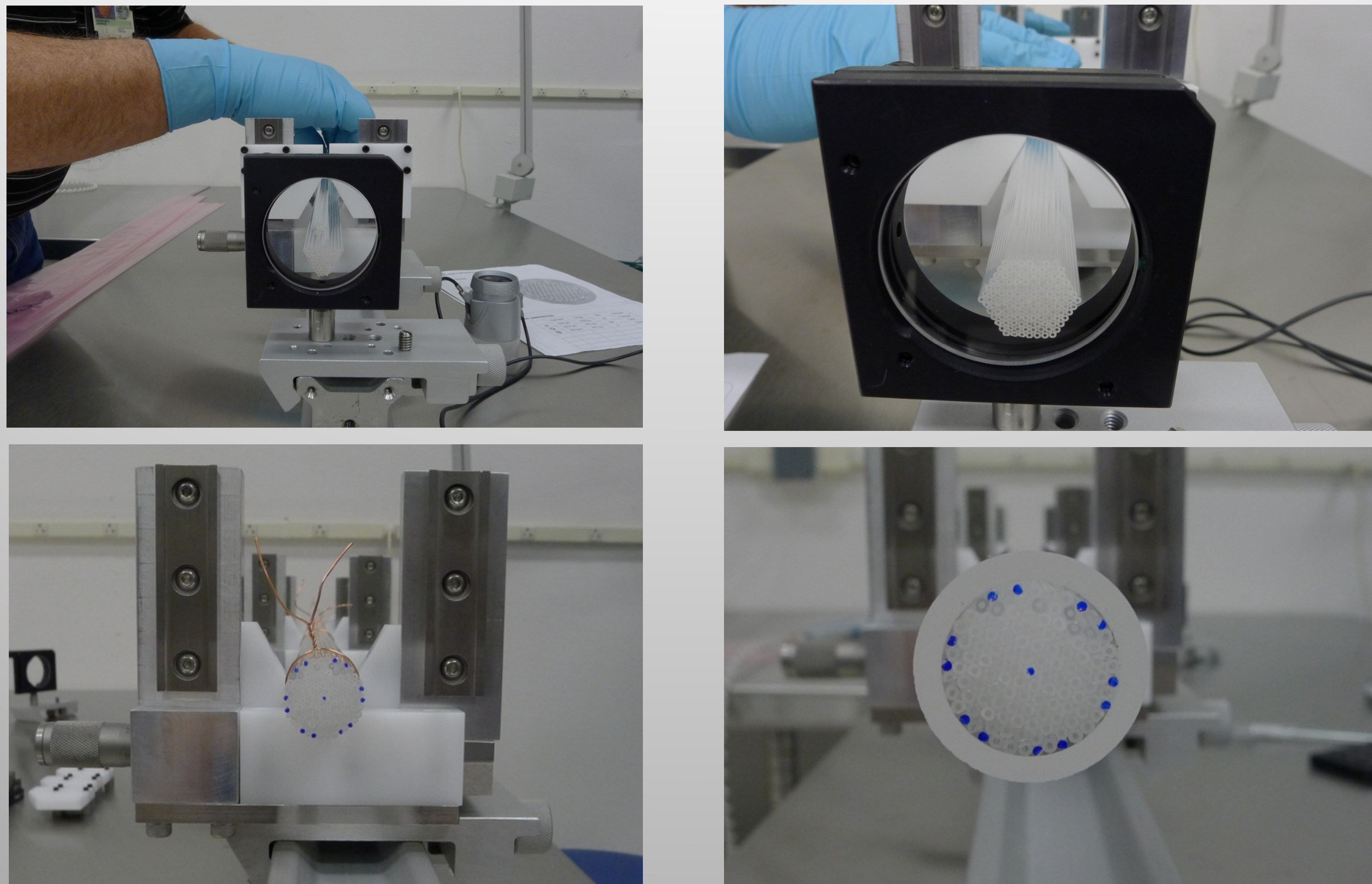




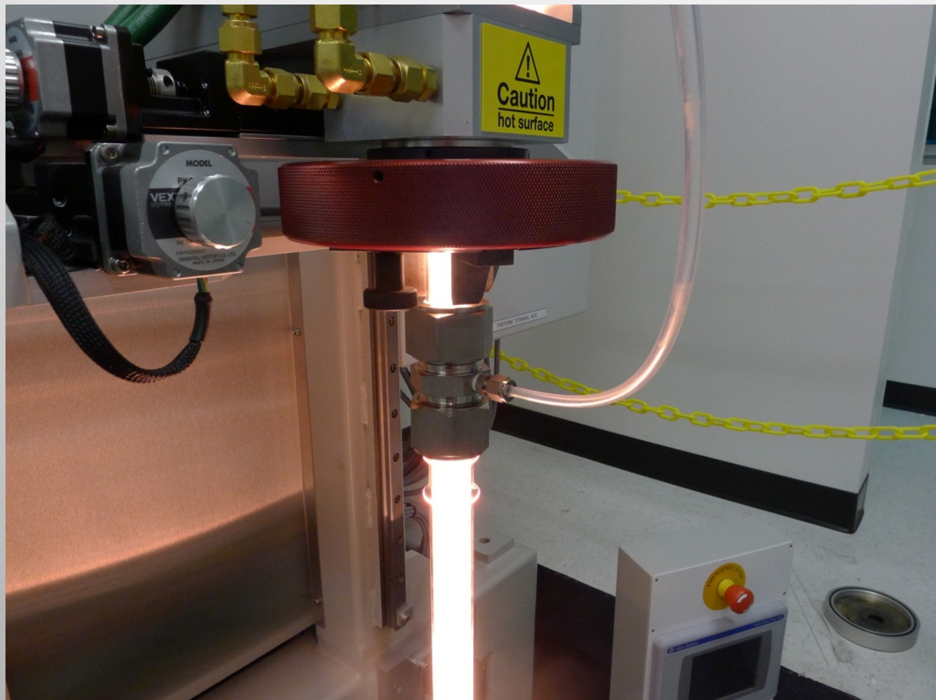
Stock silica is drawn to the dimensions for manufacture

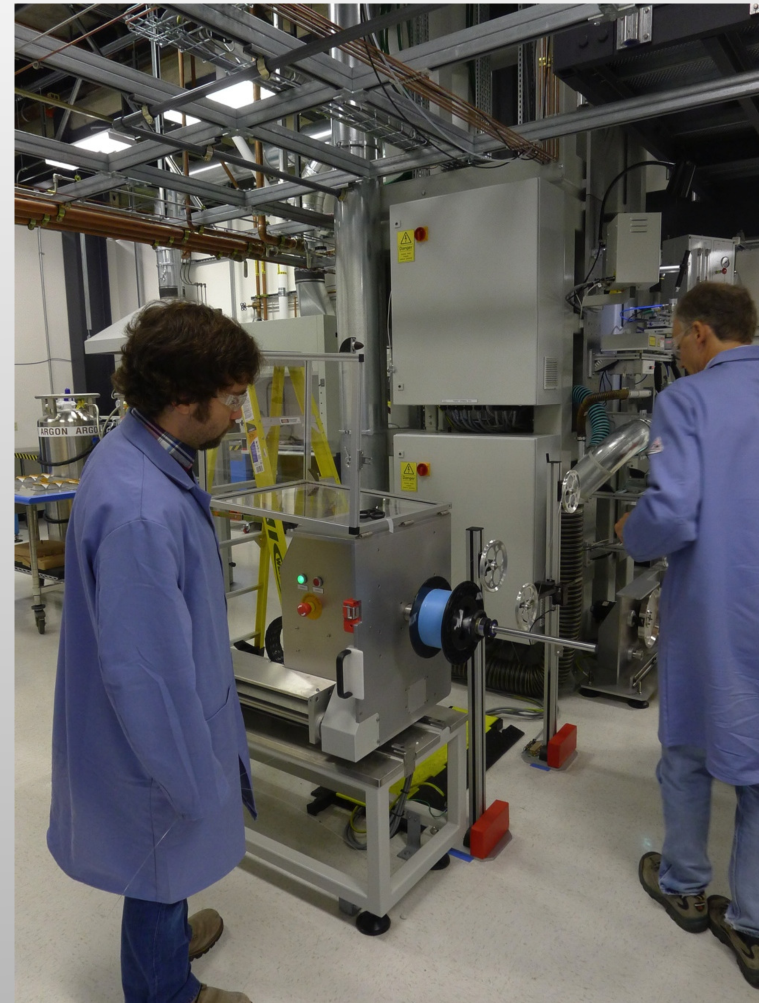


1 to 3 mm canes are stacked and sleeved into a preform



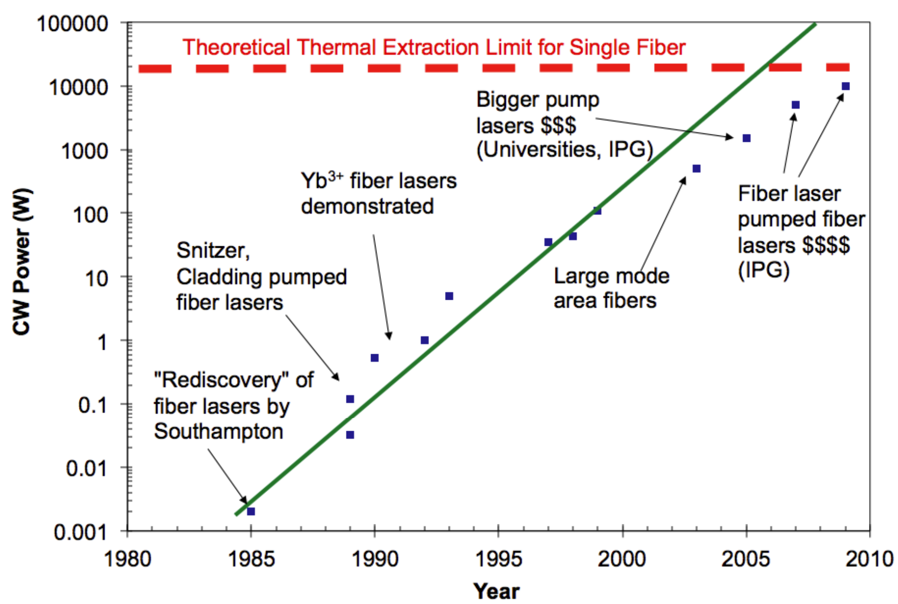
Pressure, vacuum and heat convert the preform into an optical fiber



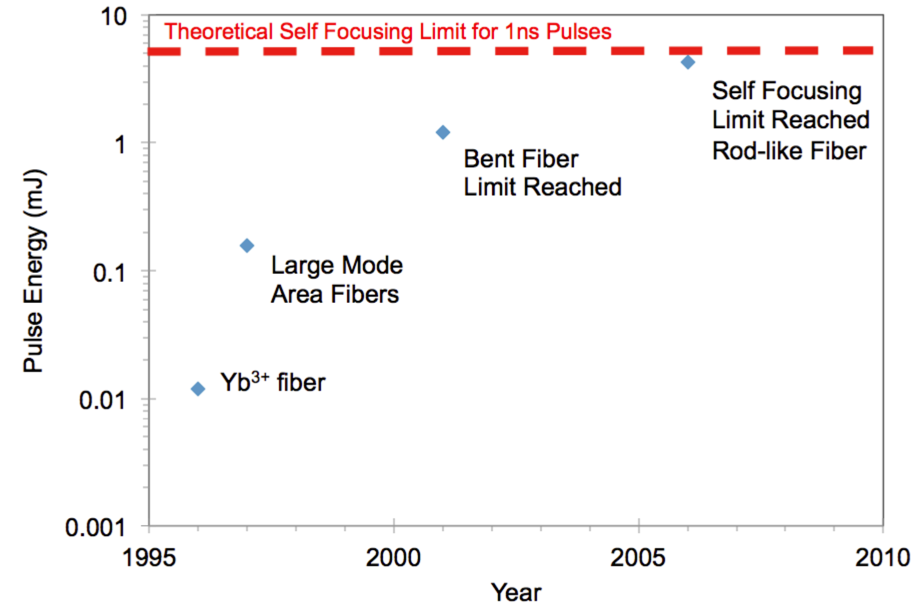


Standard fiber lasers are limited in average power and pulse energy, but we are exploring ideas for improvement

Average Power vs. Year



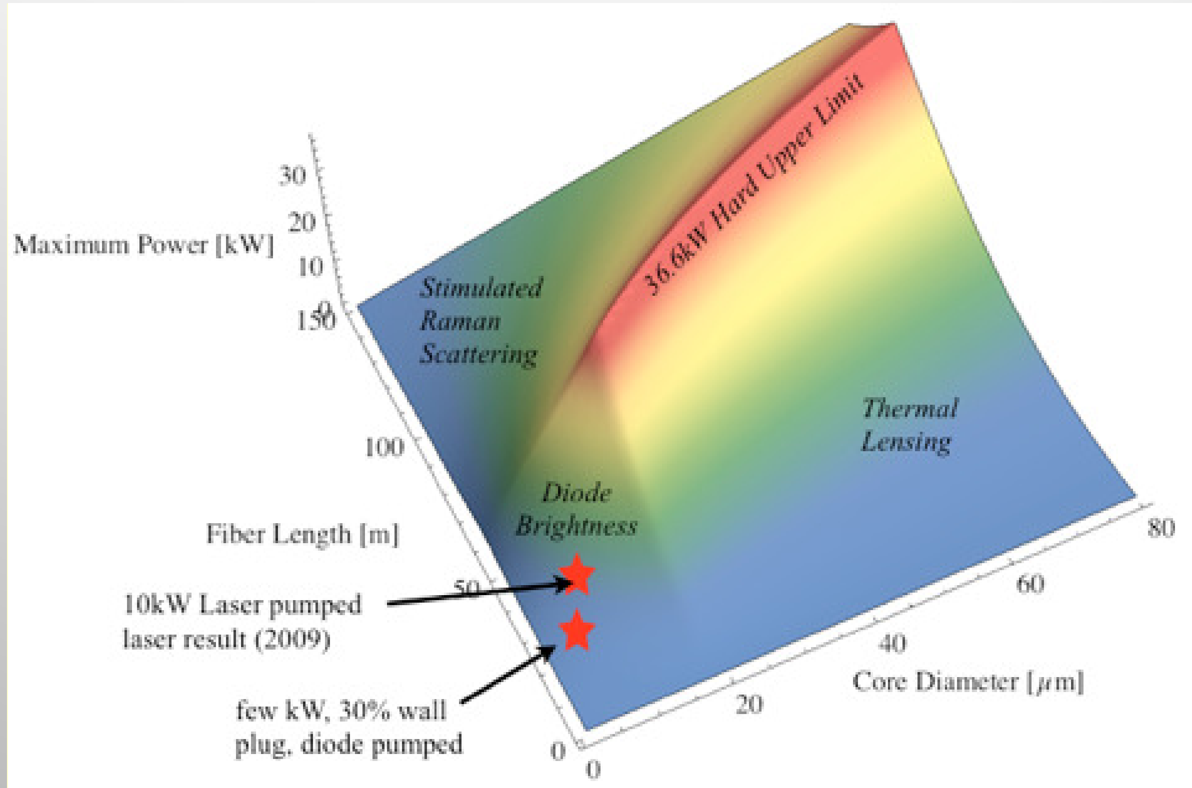
Pulse Energy vs. Year



- Little to no progress in diffraction limited single aperture power or energy scaling has been reported in 4-5 years!
- R&D focus has shifted to beam combination as limits of conventional fibers have effectively been attained

Novel waveguides offer the potential for improvements

We authored a key study on fiber laser power scalability

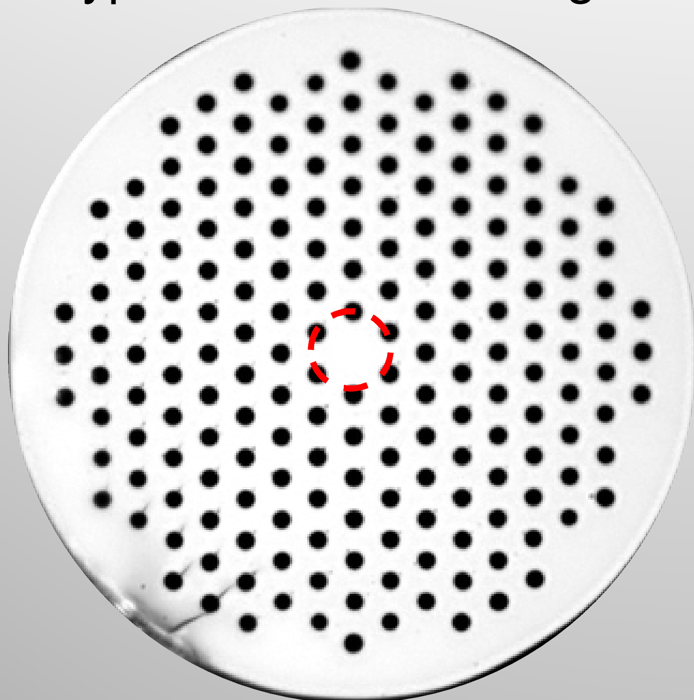


>160 citations to date with high impact in the directed energy weapons community

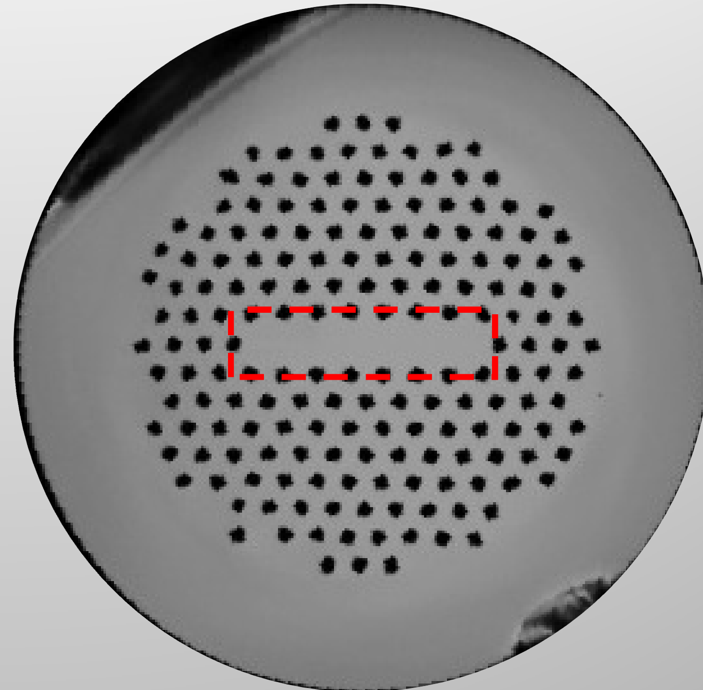
J.W. Dawson et al., "Analysis of the scalability of diffraction-limited fiber lasers and amplifiers to high average power," Optics Express vol. 16, pp. 13240-13266 (2008)

The power scaling limits may be overcome with a slab waveguide

Typical Circular Waveguide



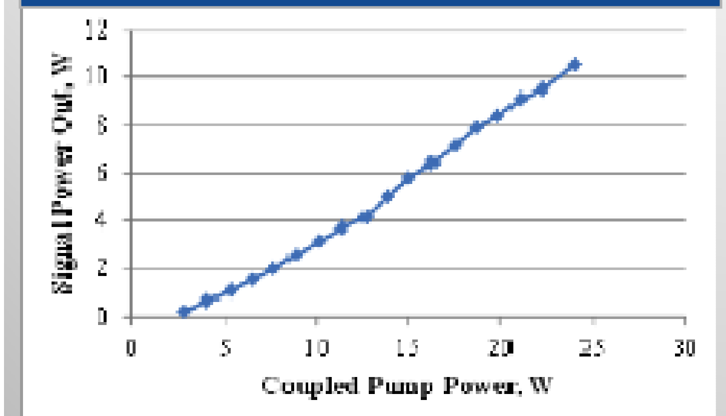
LLNL Slab Waveguide



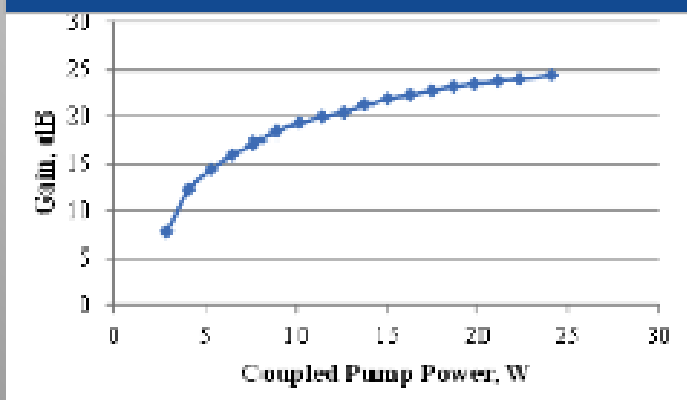
Slab waveguides permit 1-D heat flow, preferential bending perpendicular to the short axis and aperture scaling parallel to the long axis

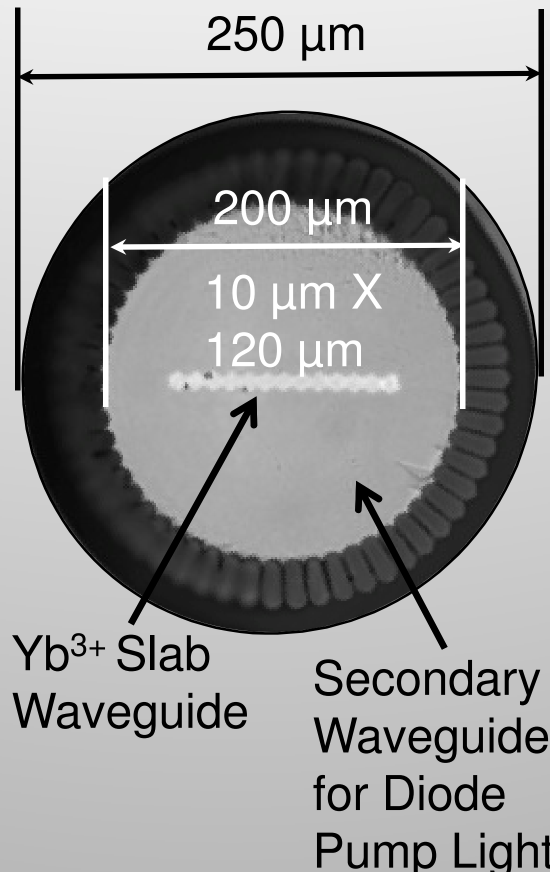
A Yb^{3+} doped slab waveguide shows stable laser amplification

10 W at 50% optical efficiency

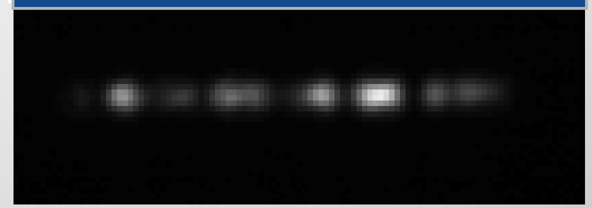


25 dB Gain (>300X)

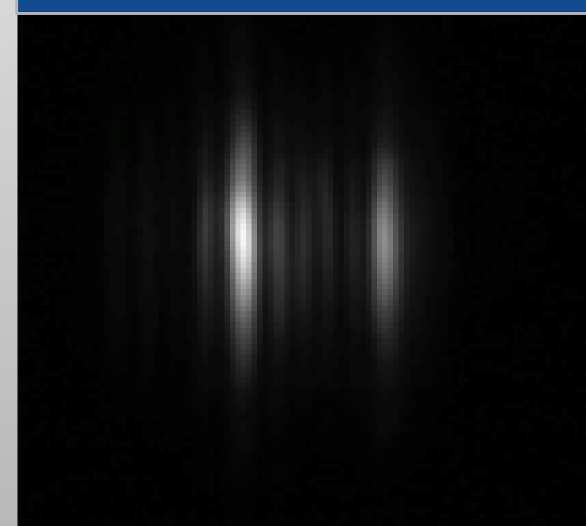




Optical Near Field



Optical Far Field



Modes are transformed to diffraction limited beams via diffractive optics

Winner 2013 R&D 100 Award!

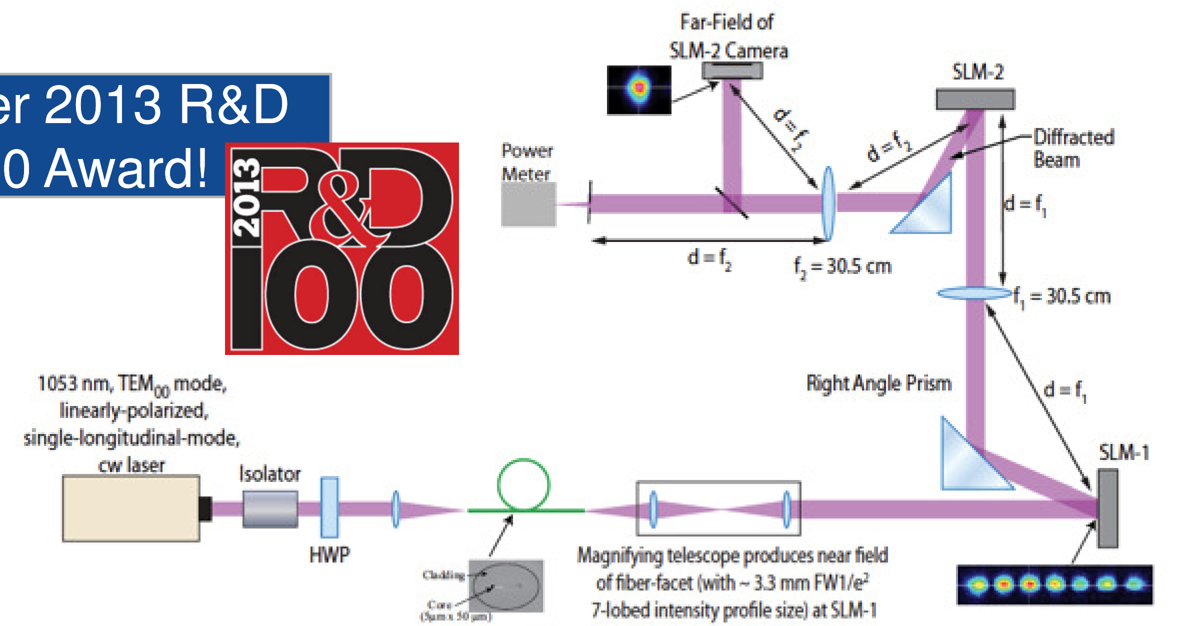
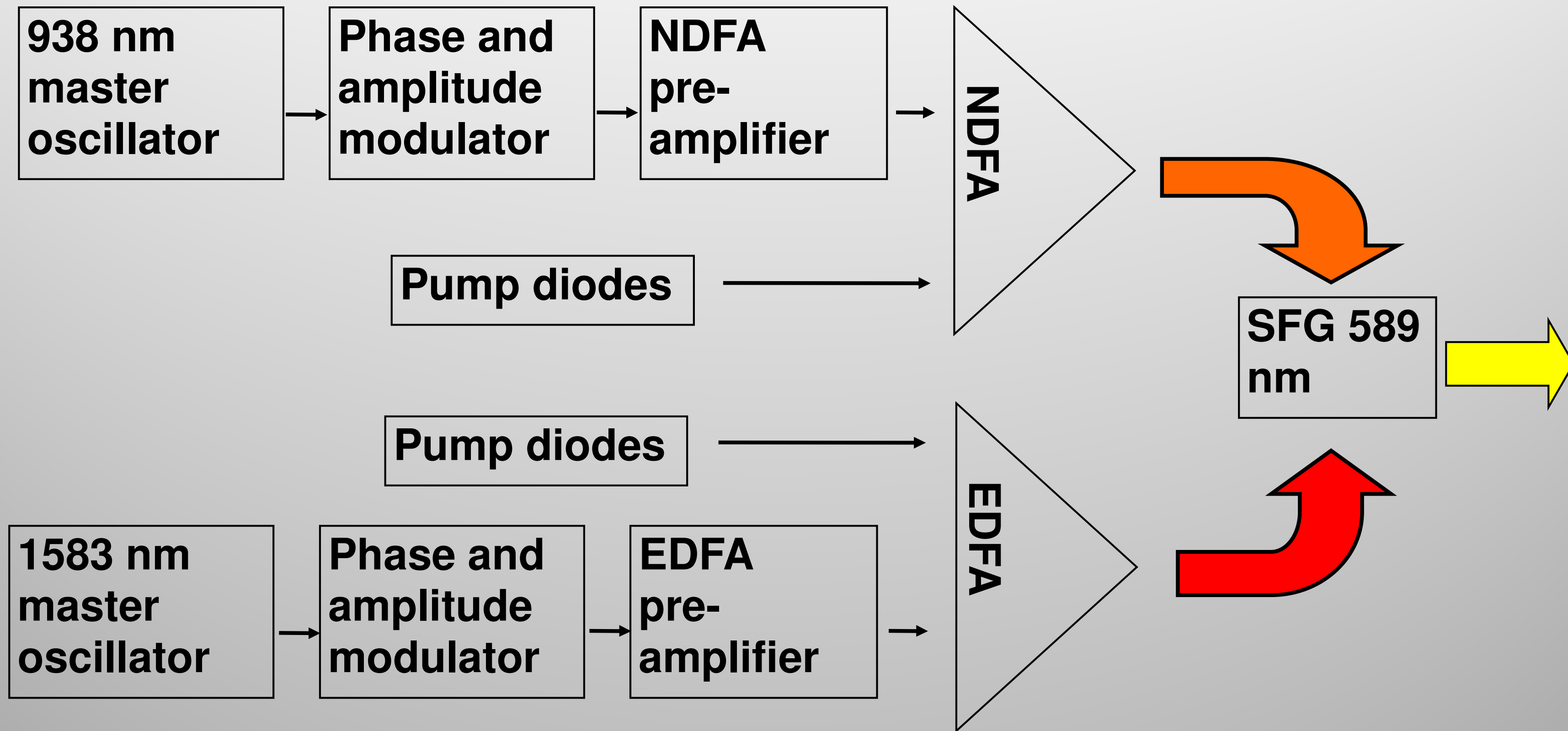


Fig. 7. Experimental schematic of the mode-converter system which uses two diffractive optic elements.

Outside interest has already been expressed in this technique via forthcoming blurb in Laser Focus World and interest in collaborations

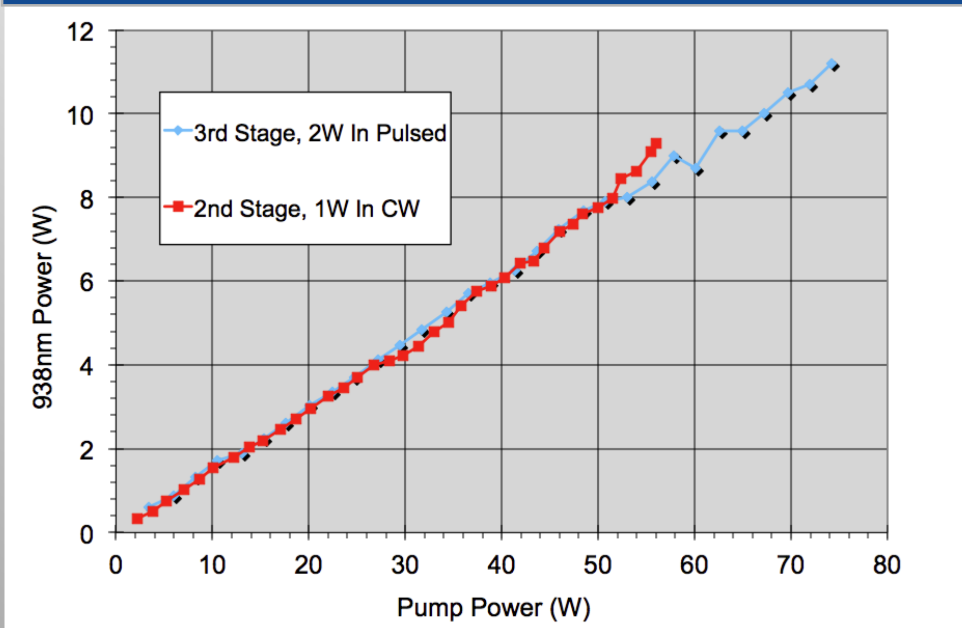
A.K. Sridharan, et al., “Mode-converters for rectangular-core fiber amplifiers to achieve diffraction-limited power scaling,” Optics Express, vol. 20, pp. 28792-28800 (Dec 2012)

We have developed fiber lasers for 589 nm guide star laser systems

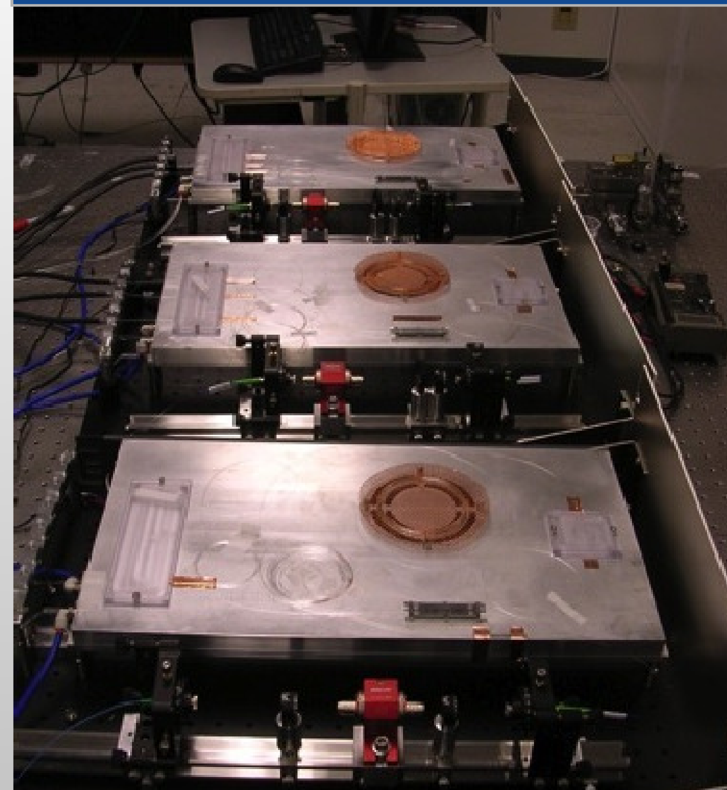


A key challenge was development of 900 nm fiber lasers

Host quality yields low efficiency at 938nm, but other glass compositions can attain 50%



Nd^{3+} PM fiber amplifier chain



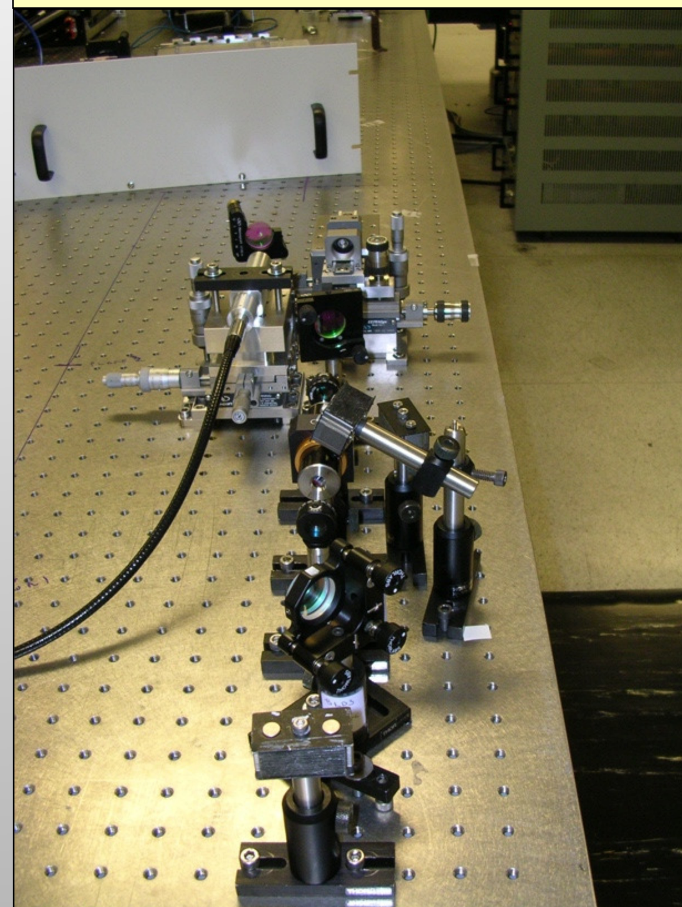
The challenges were suppression of lasing at 1µm, lack of an industrial base at the 900nm wavelength and a difficult to fabricate glass composition.

The project also required 17 W of pulsed power at 1583nm

100mW single frequency 1583 nm seed laser with PZT tuning

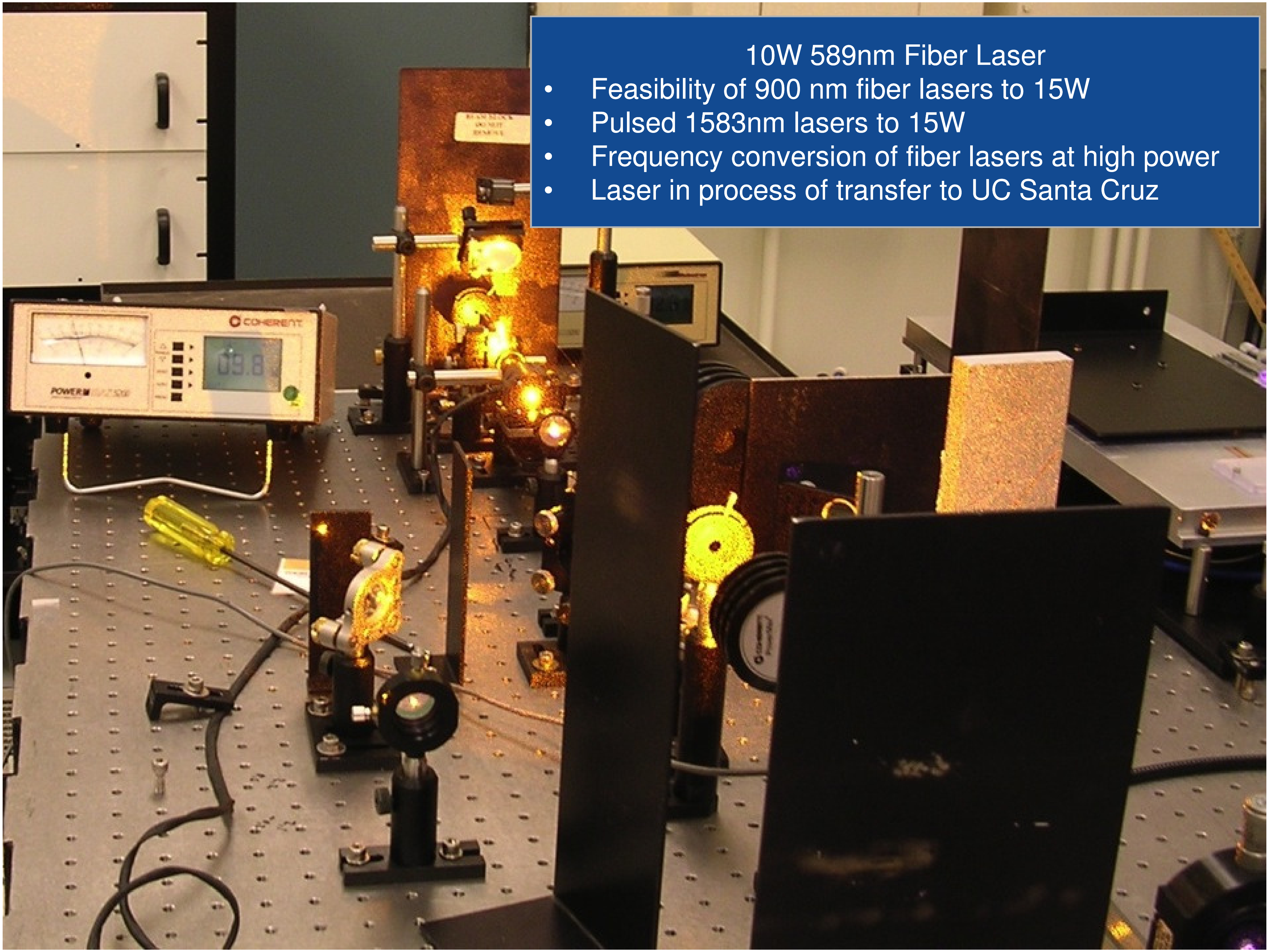
Amplitude and phase modulators and pre-amplifier module

A 30W 1545 nm commercial fiber laser resonantly pumps the Er^{3+} fiber



10W 589nm Fiber Laser

- Feasibility of 900 nm fiber lasers to 15W
- Pulsed 1583nm lasers to 15W
- Frequency conversion of fiber lasers at high power
- Laser in process of transfer to UC Santa Cruz



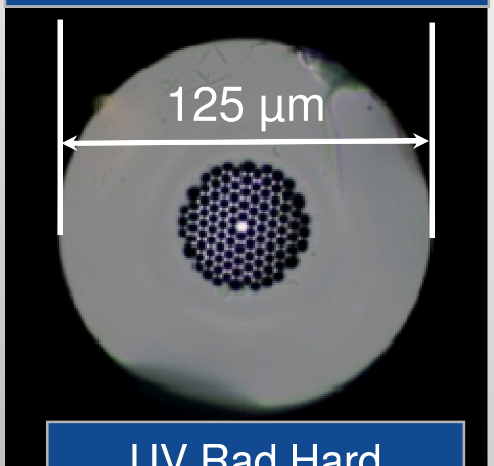
Summary

- LLNL has a wide range of capabilities in optical fibers and lasers
- We are focused primarily on pulsed fiber laser systems for a variety of applications; injection seed lasers, lasers for accelerators, other scientific applications
- We have established the capability to make micro-structured optical fibers and foresee many interesting new possibilities in this area

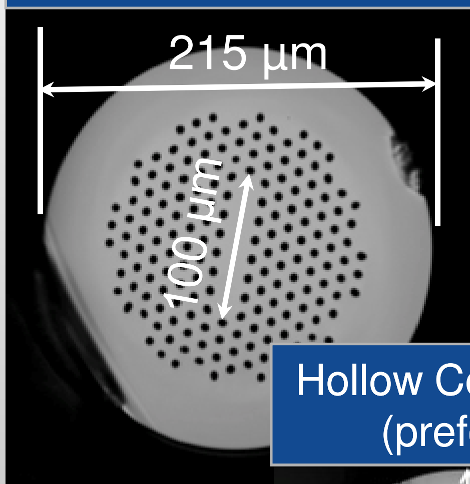
Lawrence Livermore
National Laboratory

We have demonstrated the capability to make a wide variety of fibers

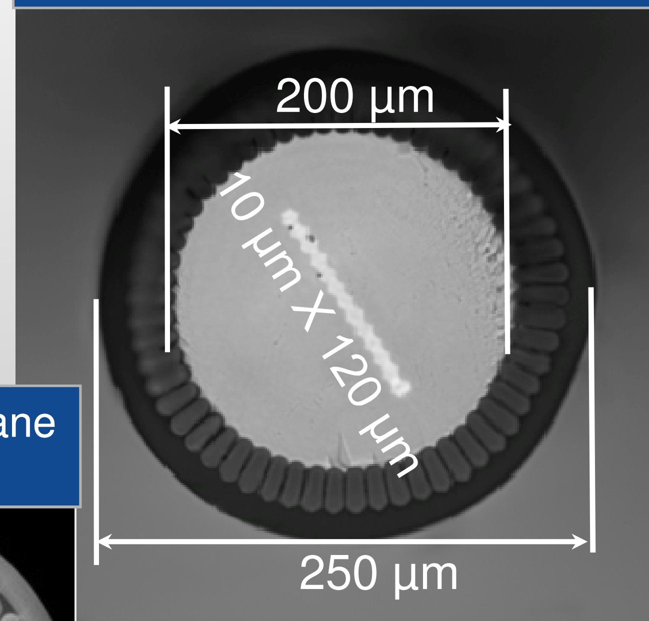
First fiber small core



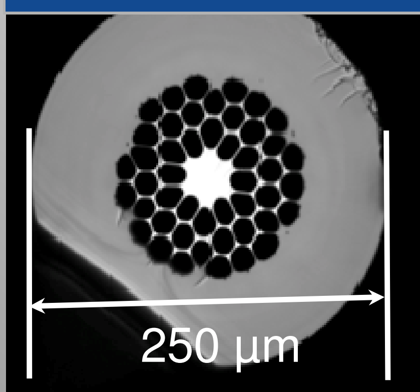
1st Passive Ribbon Fiber



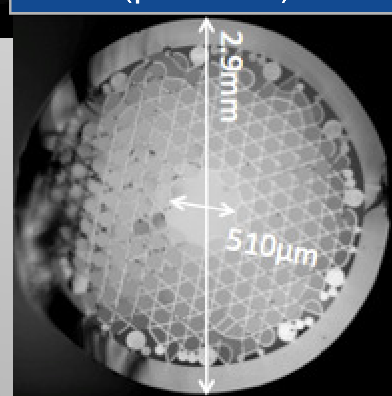
1st Yb^{3+} Doped Ribbon Fiber



UV Rad Hard Qualification Fiber

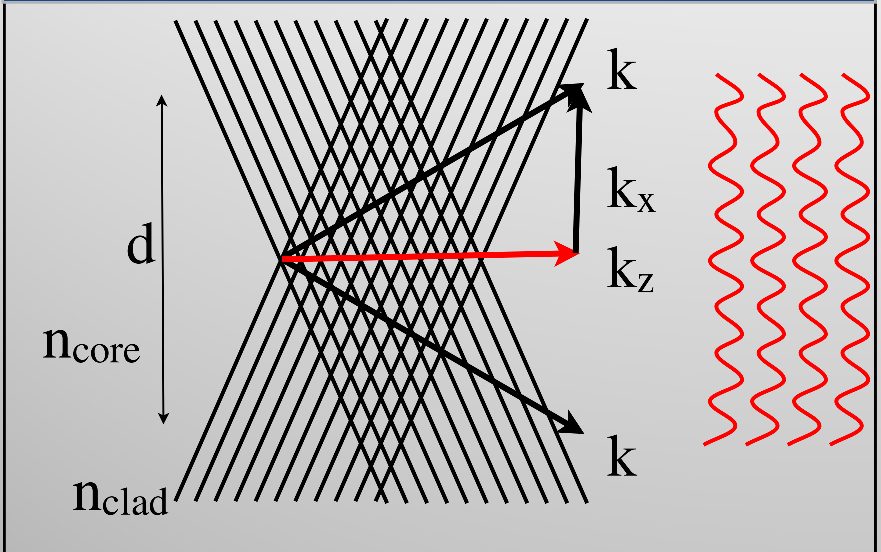


Hollow Core Cane (preform)



Beam quality on the long axis is stabilized via a higher order mode

Higher order modes can be thought of as the interference of 2 plane waves



Higher modes have different phase speeds and thus do not exchange power efficiently

$$k^2 = k_x^2 + k_z^2$$

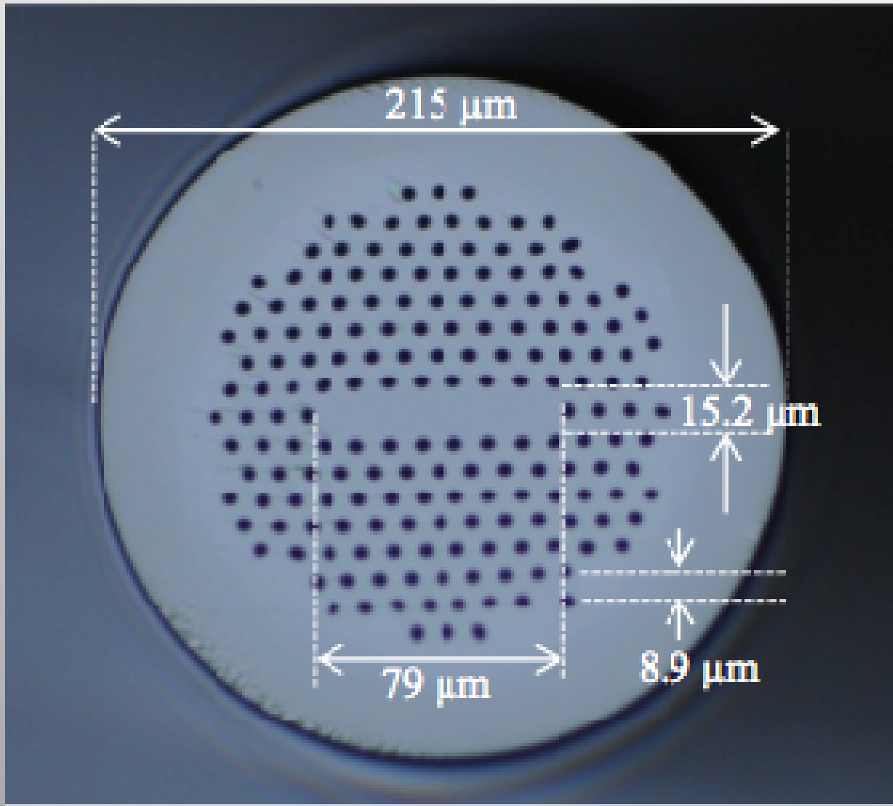
$$k_x = m\frac{\pi}{d}$$

$$n_{eff} = \frac{k_z}{k_0} = n_{core}\sqrt{1-\left(m\frac{\pi}{n_{core}k_0 d}\right)^2}$$

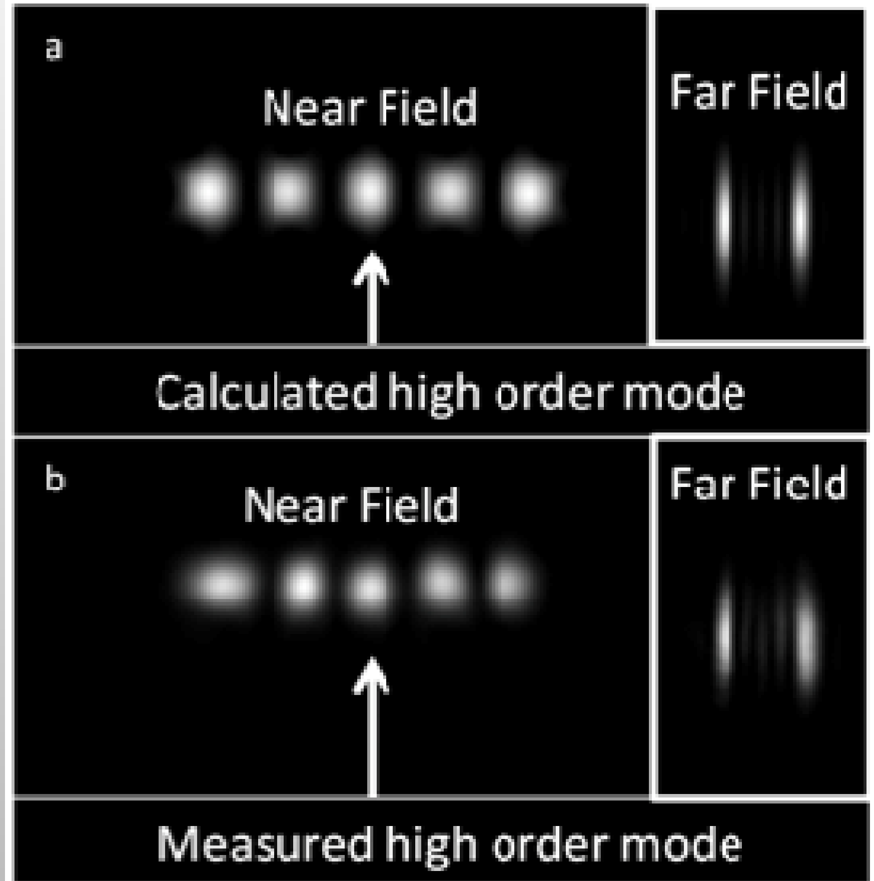
$$\frac{dn_{eff}}{dm} \approx -\frac{m}{n_{core}}\left(\frac{\pi}{k_0 d}\right)^2$$

A key challenge has been efficient transformation between these higher order modes and diffraction limited beams

Our optical fiber facility enabled us to fabricate slab waveguides



LLNL Fabricated PCF Ribbon Fiber



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