



Scaling of High Average Power Fiber Lasers at Stanford

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Outline



- Introduction
 - High power fiber amplifier applications
 - Pros and cons of fiber amplifiers
- Software model and experimental verification
- 200 W fiber amplifier design
- Scaling to kW class fiber lasers – phosphates



High power fiber amplifier applications



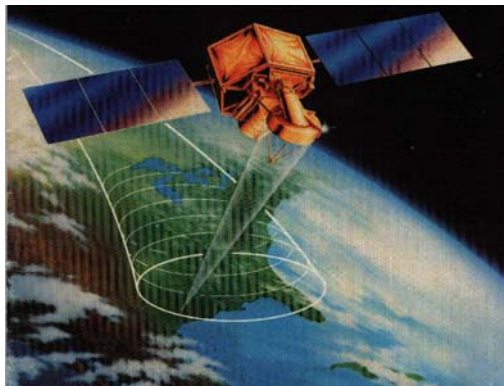
	LIGO I (Now)	Advanced LIGO (2007)
Laser requirements	10 W TEM ₀₀ @ 1.06 μm Single axial mode Single polarization	165 W TEM ₀₀ @ 1.06 μm Single axial mode Single polarization
Laser architecture	Solid state MOPA	Undecided

• Phase-locking modelocked fiber oscillators

- Laser Particle Acceleration
- Advanced precision weaponry
- Optical clock

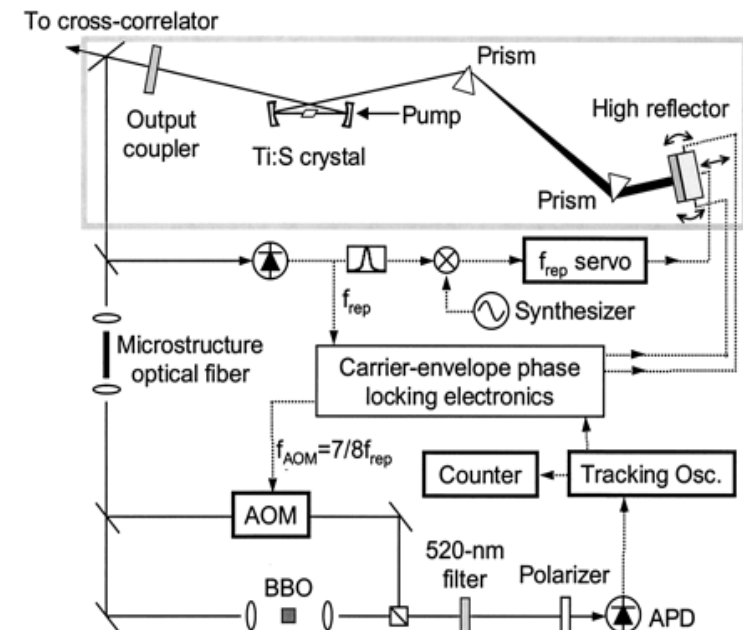
• High power fiber preamplifiers

- Remote sensing



Artist's conceptual design of satellite based remote sensing

Optical phase stabilization of ML laser,
D. J. Jones et al., Science, 2000.





Fiber Laser Architecture



Pros and cons

- Advantages
 - Highly efficient
 - Smaller heat dissipation
 - Good transverse mode quality
- Disadvantages
 - lower thermal conductivity
 - Nonlinear effects can limit output power

Challenges

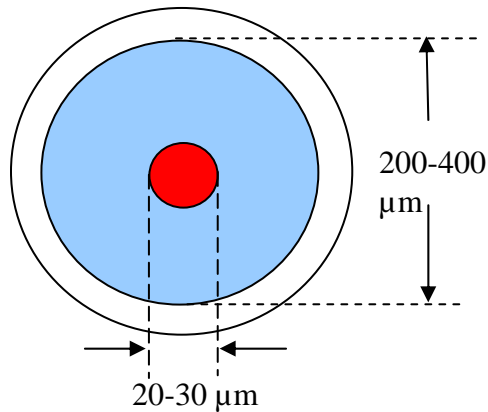
- Coupling pump into fiber
 - Single mode fiber coupled diode laser pumps are limited to ~ 1 W
 - Solution: Couple multimode pumps**
- Nonlinear effects
 - Undesirable nonlinear effects (SRS, SBS) scale approximately with product of interaction length and average intensity
 - Solution: Increase core area**



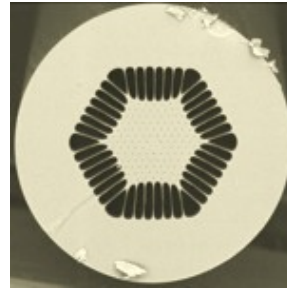
Large Mode Area Double Clad Fiber



LMA Fiber Types

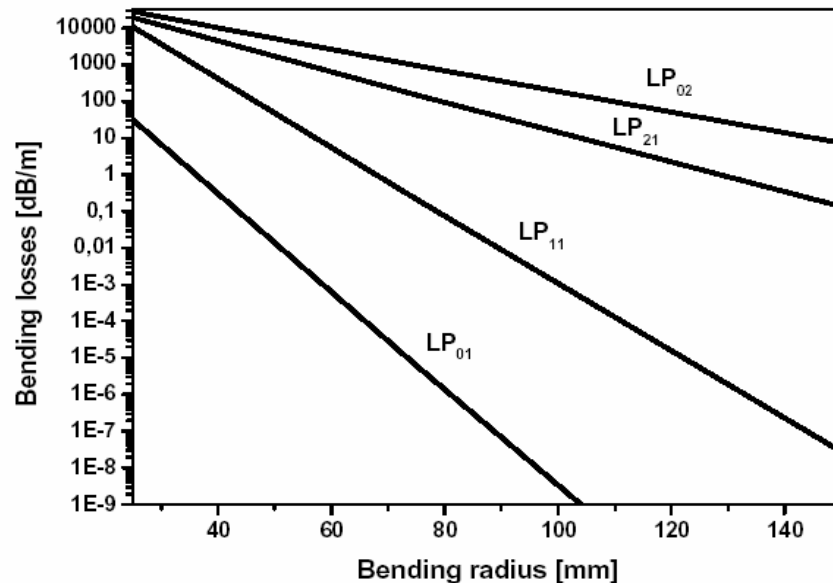


Standard LMA Fiber



-Crystal-Fiber LMA fiber
Holey LMA Fiber

- Inner cladding permits multimode pumps to be coupled into fiber
- Large mode area decreases average intensity in fiber



- Maintain spatial mode by employing differential bending losses



Fiber Amplifier Modeling



Our software predicts amplifier output power versus pump power, fiber length, ion doping, etc.

Code also calculates

- ASE power and spectrum
- Polarization properties
- Nonlinear effects
- Temperature distribution

Differential equation*:

$$\frac{d\vec{S}_v(z)}{dz} = \left(\vec{g}_v(z) + \vec{b}_v(z) + \vec{l}_v(z) \right) \vec{S}_v(z) + \vec{E}_v(z)$$

Stokes vector components $\vec{S}_v(z)$

Birefringence tensor $\vec{b}_v(z)$

Spontaneous emission factor $\vec{E}_v(z)$

Mueller Gain Matrix $\vec{g}_v(z)$

Background loss $\vec{l}_v(z)$

*Wagener et al., JLT 1998

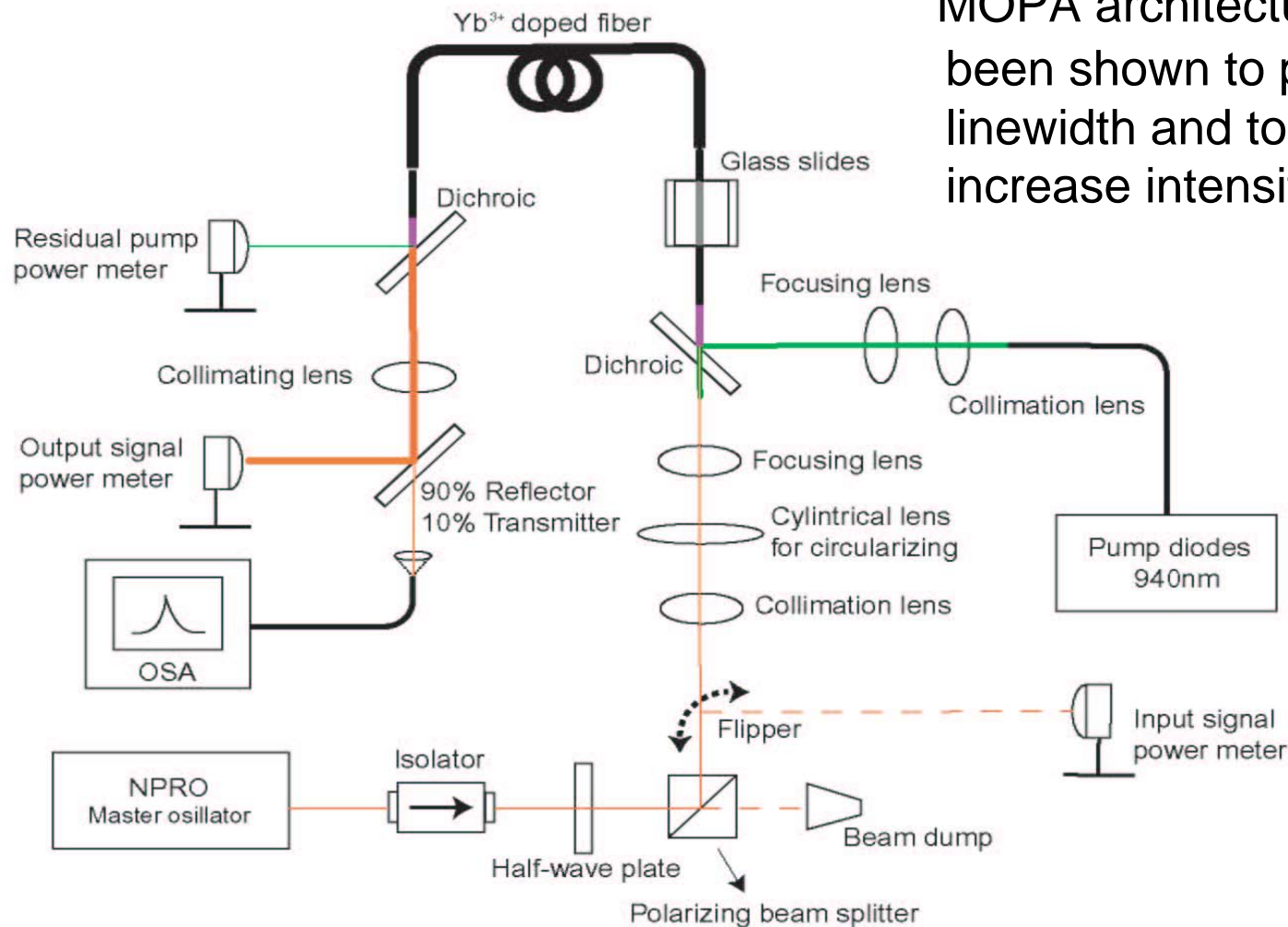


10 W experimental verification



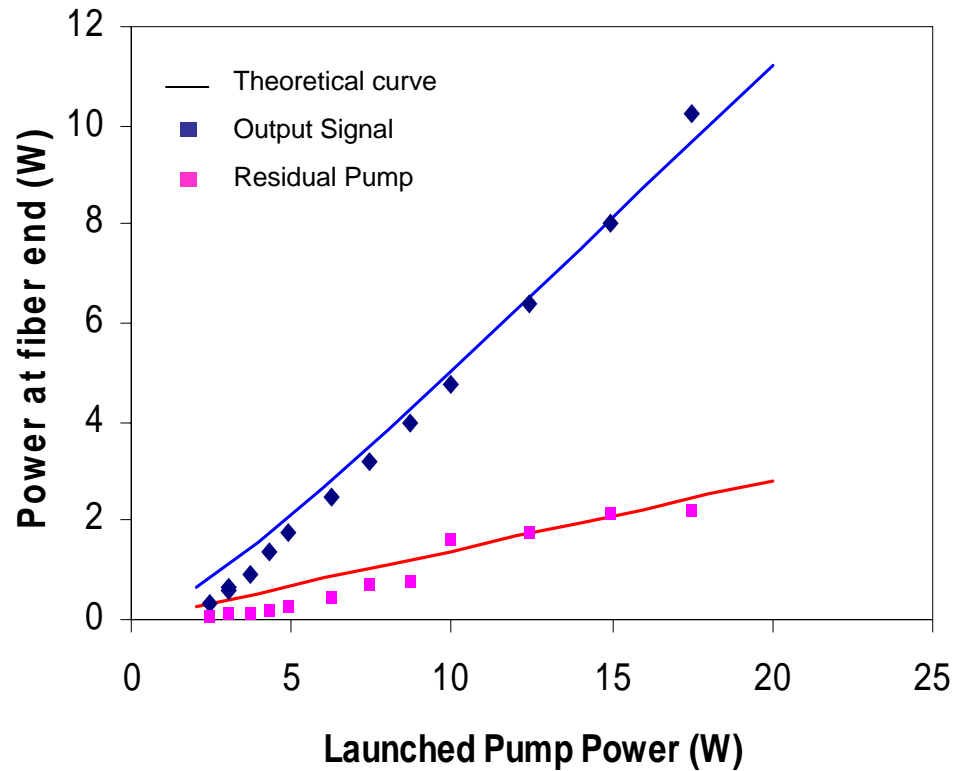
- Experimental set up

MOPA architecture in fiber has been shown to preserve NPRO linewidth and to not appreciably increase intensity noise

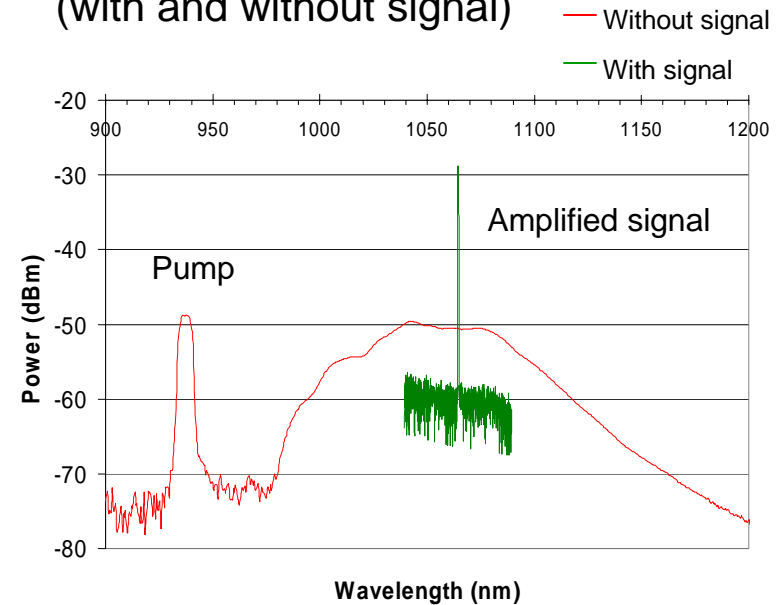




10 W experimental results



Output spectrum at 3 W launched pump (with and without signal)



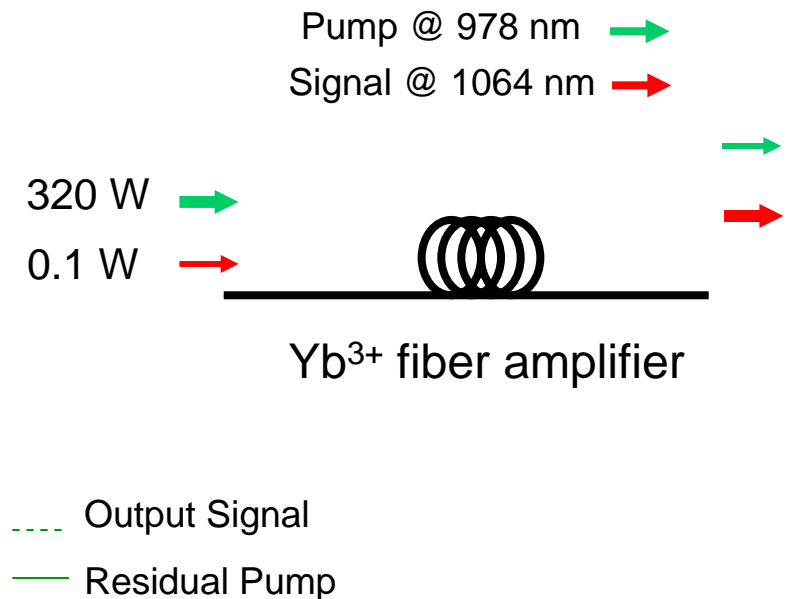
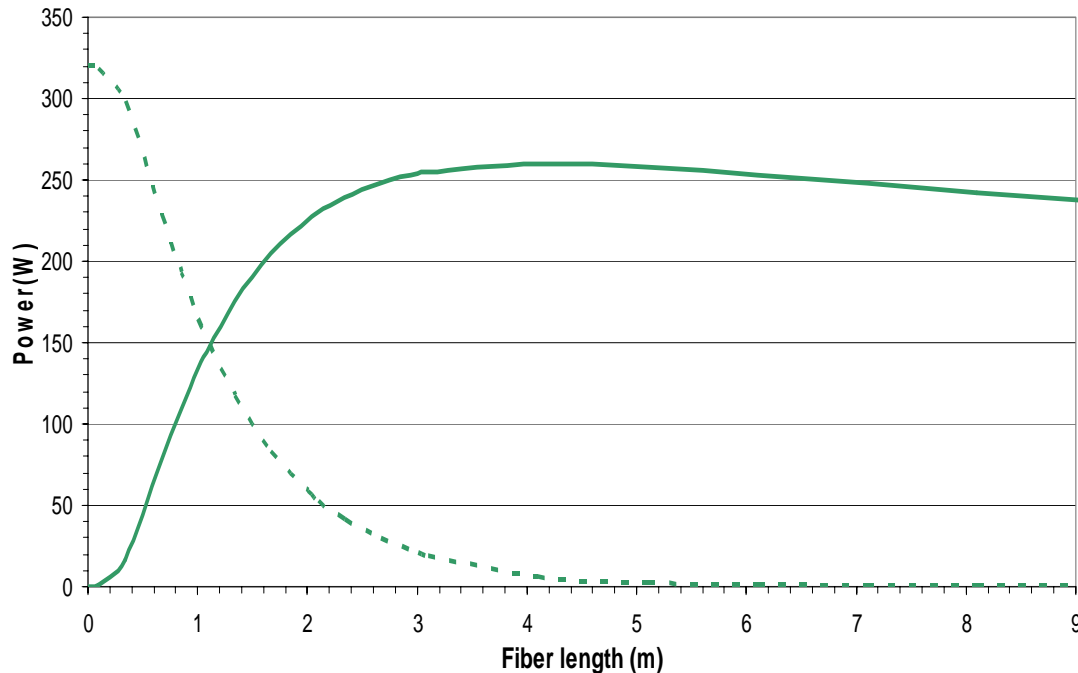
- 10.3 W of output power observed before fiber burned
- 67% optical to optical efficiency with respect to absorbed pump
- Calculated temperature of 59.7°C at core-cladding interface



250 W simulation (Single Pass Pump)



Power curves
(30 μm core, 250 μm cladding)



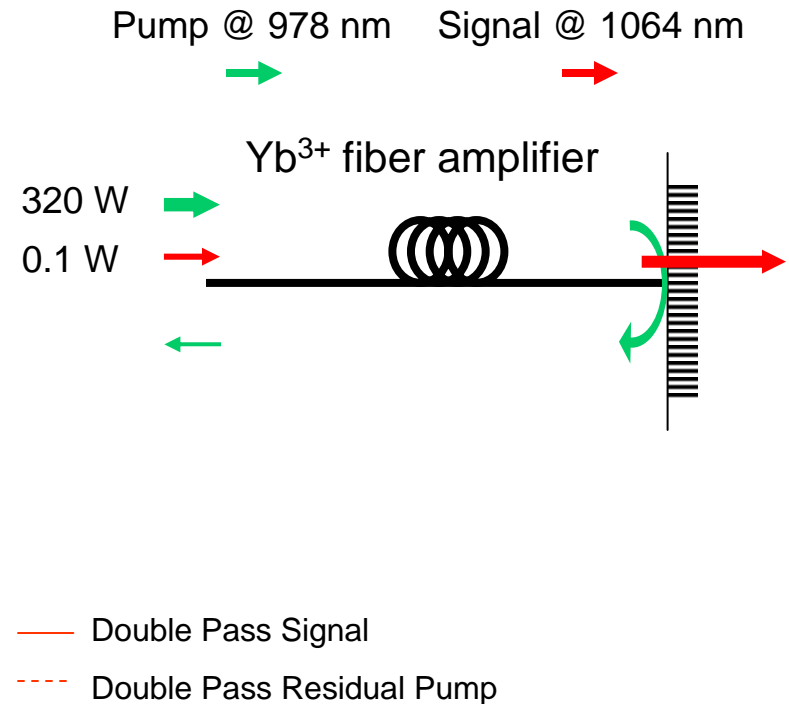
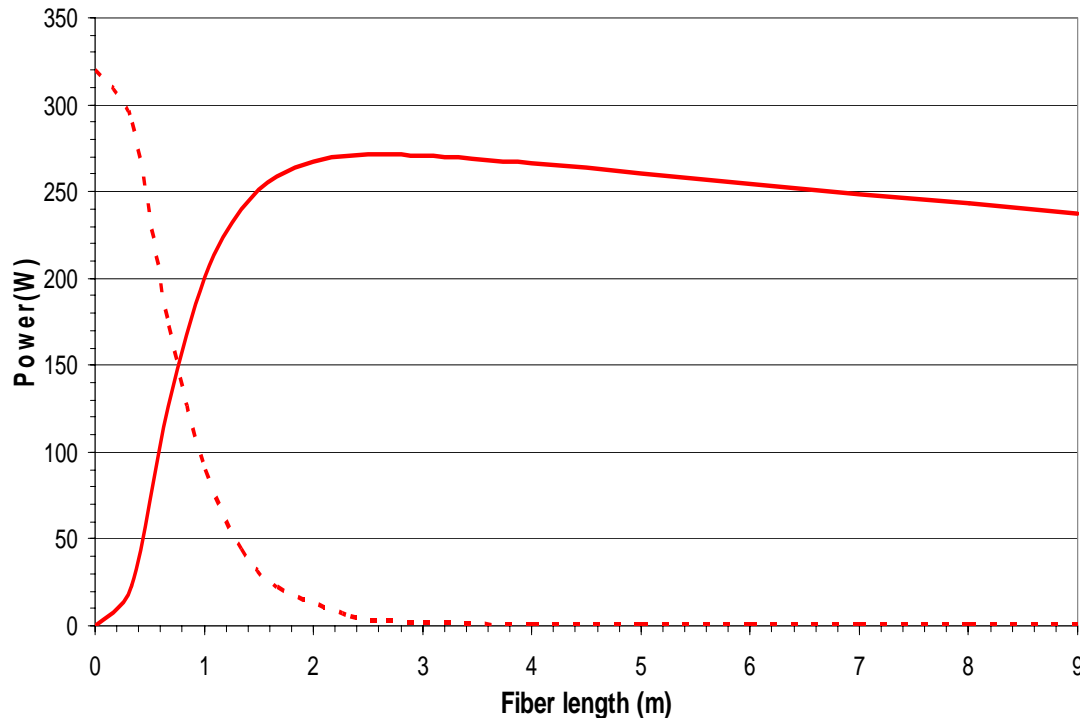
- 250 W of output reached at length of 2.8 meters of commercially available LMA PM fiber (11 dB/m small signal absorption at 978 nm)
- Simulated temperature at core-cladding interface of 127°C using only natural convection
- **Output power meets Advanced LIGO specifications**



250 W simulation (Double Pass Pump)



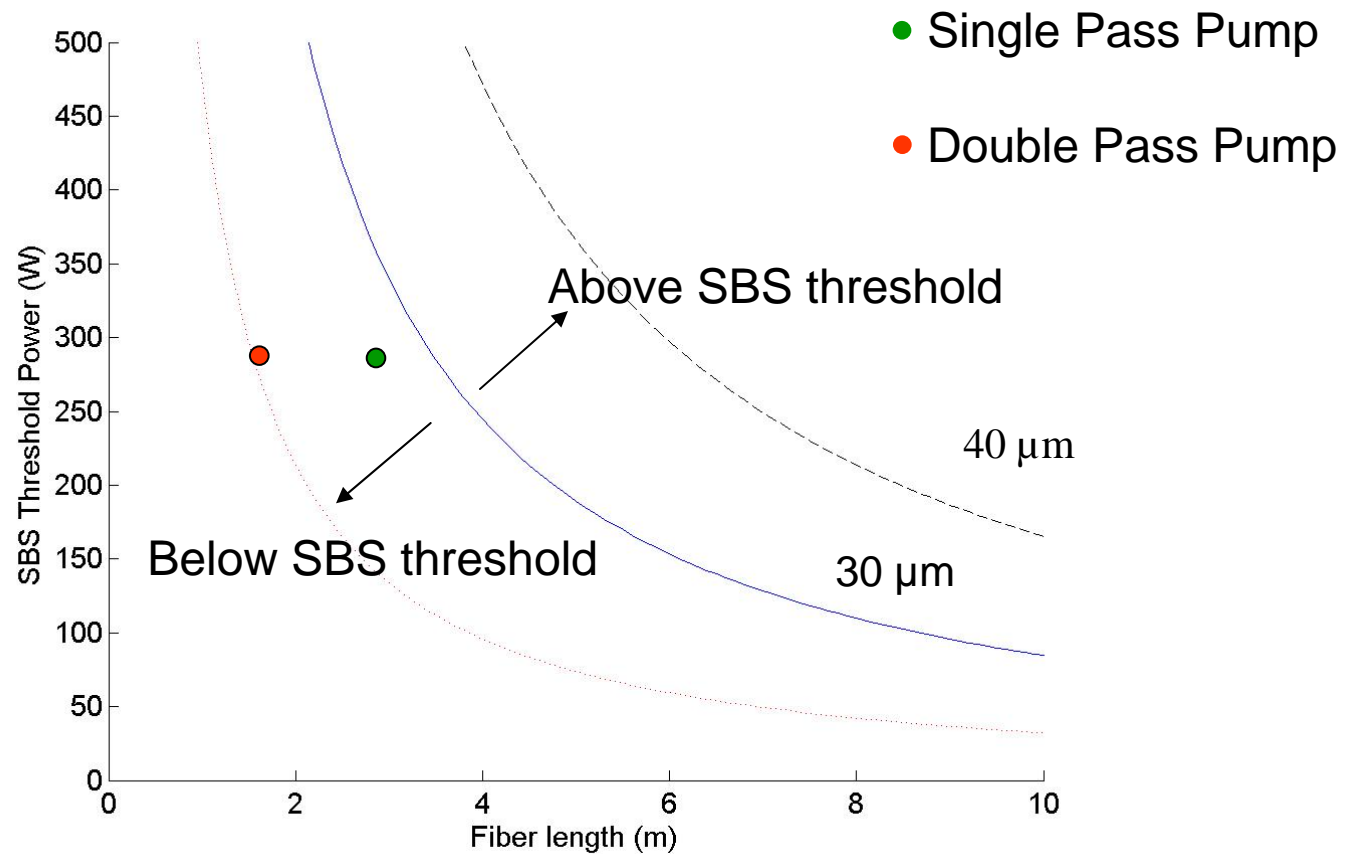
Power curves
(30 μm core, 250 μm cladding)



- 250 W of output reached at fiber length of 1.5 meters
- Simulated temperature at core-cladding interface of 198°C using only natural convection – more aggressive cooling required



250 W simulation (Nonlinear effects)



Both single passed pump and double passed pump designs are below the Brillouin threshold for their respective lengths

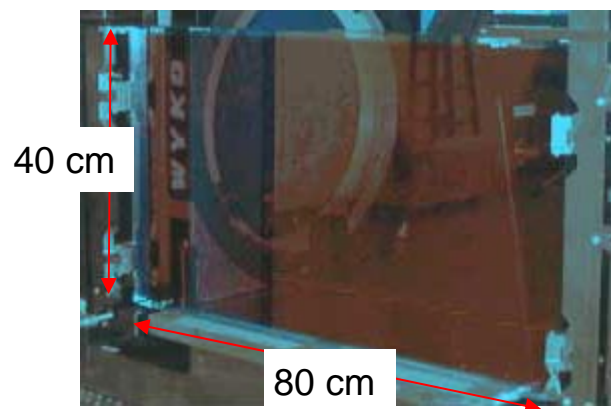


kW Class Fiber Amplifiers – Phosphates



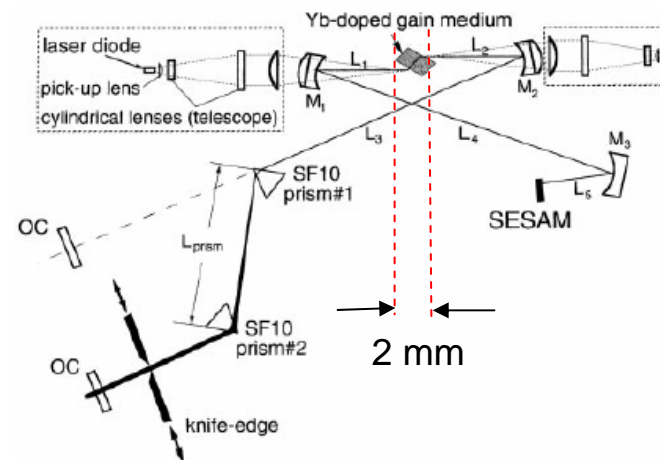
Advantages	Disadvantages
<ul style="list-style-type: none">• Can be highly doped (~20 % wt.) without lifetime quenching effects• Shorter lengths avoid nonlinear effects	<ul style="list-style-type: none">• Thermal conductivity and thermal shock resistance is not as high as silica• Immature technology compared to silica

Very Large



NIF Nd:Phosphate amplifier slabs

Very Small



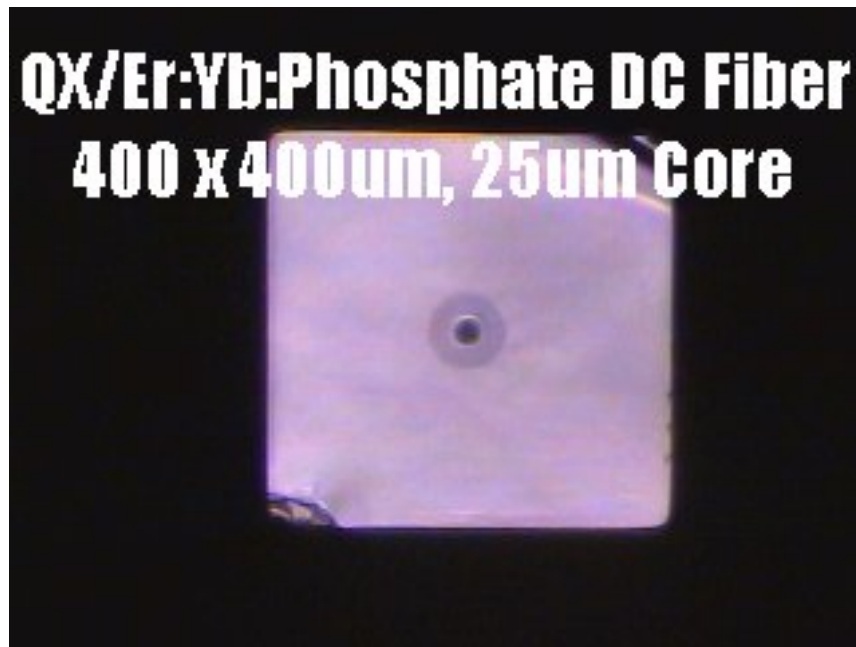
Passively modelocked oscillator



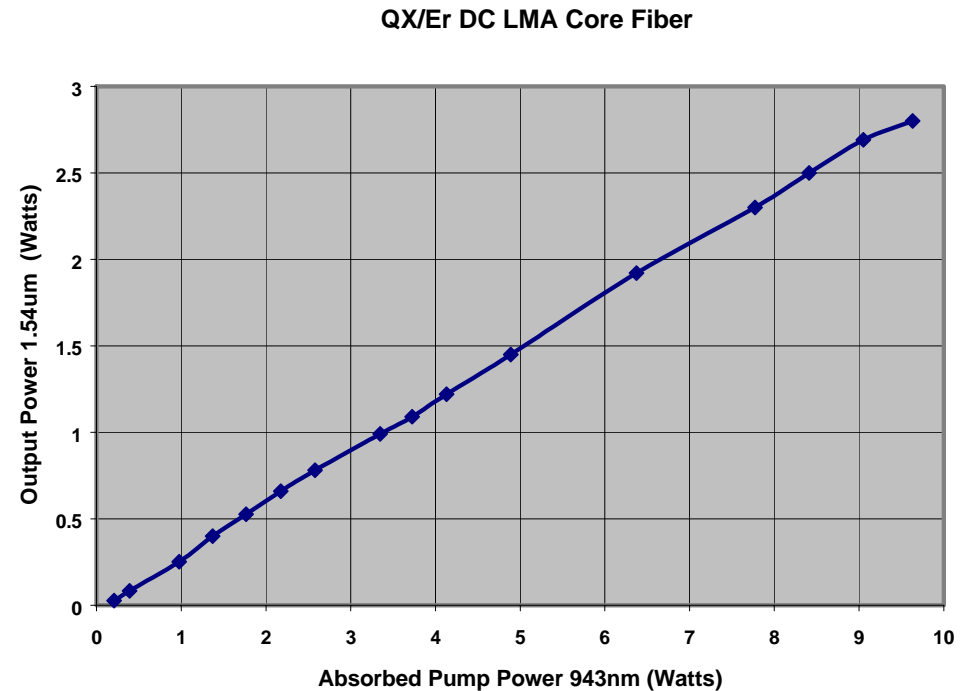
High Power Phosphate Fiber



Recent reported results:



Kigre LMA Double Clad
Erbium-Ytterbium Co-doped
Phosphate Fiber



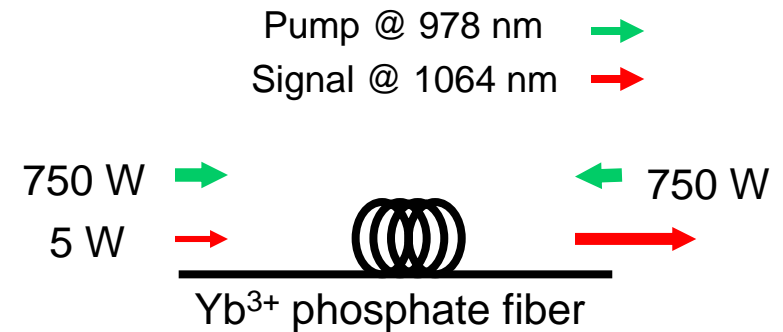
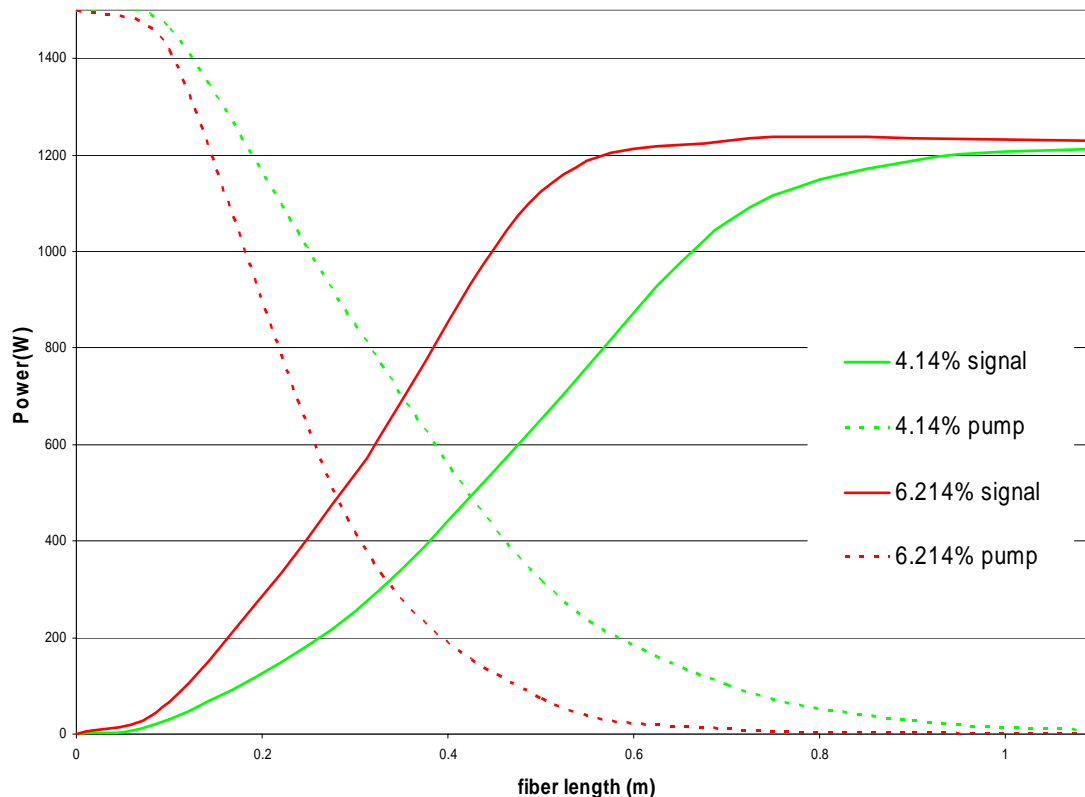
Myers et al., Photonics West 2003



Kilowatt phosphate simulations



750W double pump @ 980nm; 5W signal @1064nm



- Both the 4% wt. doping and the 6% wt. doping product produce 1 kW of power at fiber lengths below the SBS threshold for a 30 μm core
- Doping level and fiber length will have to be engineered so that temperature rise in the phosphate glass is under 600°C



Future work



-
- Experimentally use bending losses to maintain single spatial mode
 - Use silicate bonding to increase damage threshold of fiber ends
 - Demonstrate 200 W of output power
 - Investigate phosphates further
 - Investigate cooling strategies and incorporate forced convection and conduction cooling models into software



Conclusions



- We have developed and verified a software model that predicts the most important aspects of a fiber amplifier's performance
- We have presented a design for a 200 W class amplifier that will be built in the near future
- We have presented a possible pathway to developing kilowatt class, diffraction-limited, single frequency fiber sources

Acknowledgements

- DARPA and NSF for funding this work