Scaling of High Average Power Fiber Lasers at Stanford

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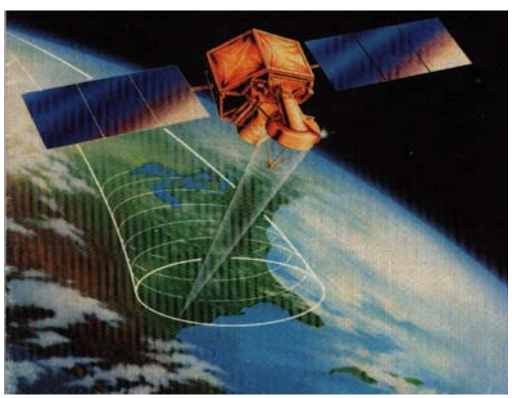
Outline

- 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

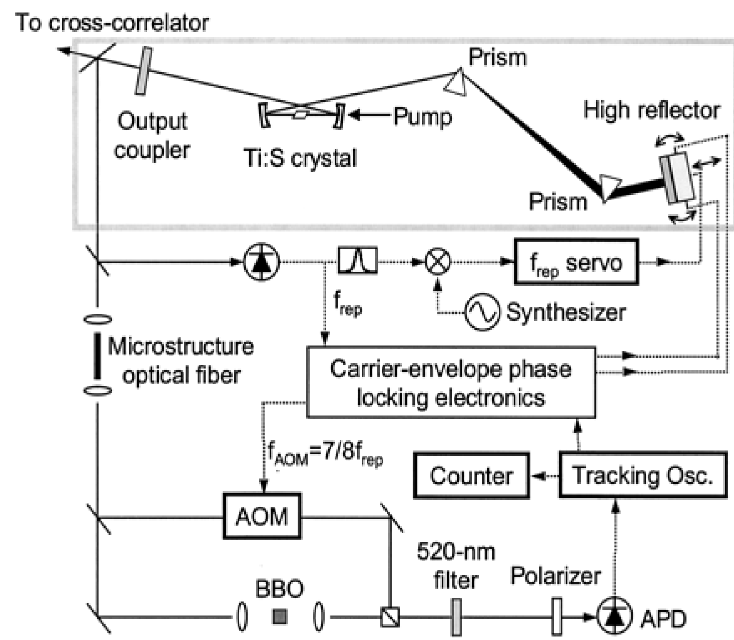
	LIGO I (Now)	Advanced LIGO (2007)
Laser requirements	10 W TEM_{00} @1.06 µm Single axial mode Single polarization	165 W TEM_{00} @ 1.06 µm Single axial mode Single polarization
Laser architecture	Solid state MOPA	Undecided

- **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

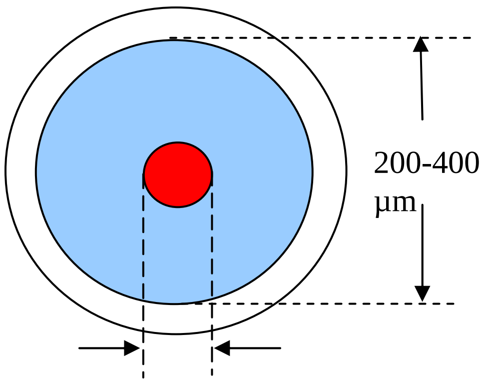
- Coupling pump into fiber
  - Single mode fiber coupled diode laser pumps are limited to ~ 1 W

  Solution: Couple multimode pumps
- Nonlinear effects
  - Undesirable nonlinear effects (SRS, SBS) scale approximately with product of interaction length and average intensity

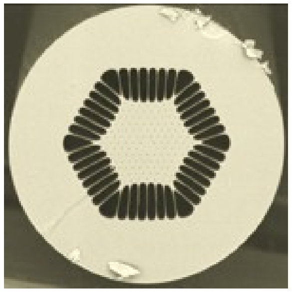
  Solution: Increase core area

Large Mode Area Double Clad Fiber

LMA Fiber Types

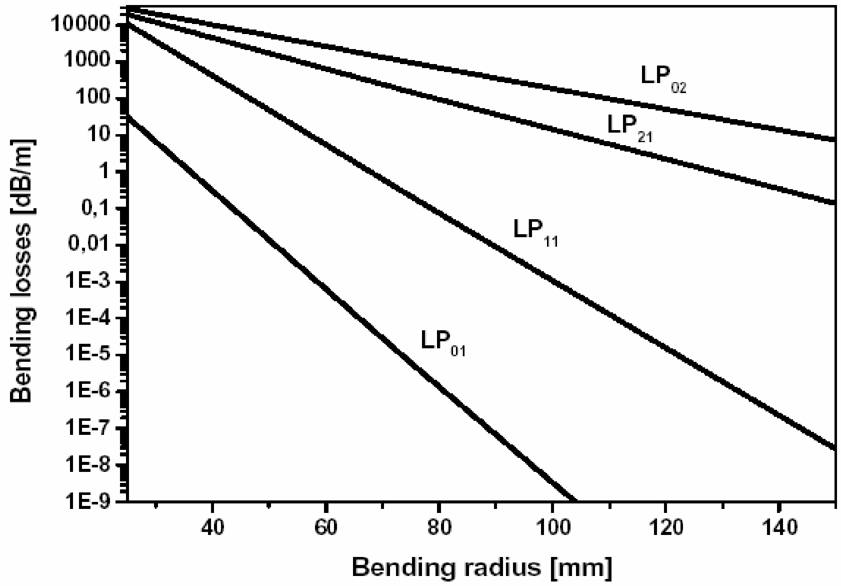


Standard LMA Fiber



-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

J. Limpert et al., Photonics West 2003

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*:

Stokes vector components

Birefringence tensor

Spontaneous emission factor

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

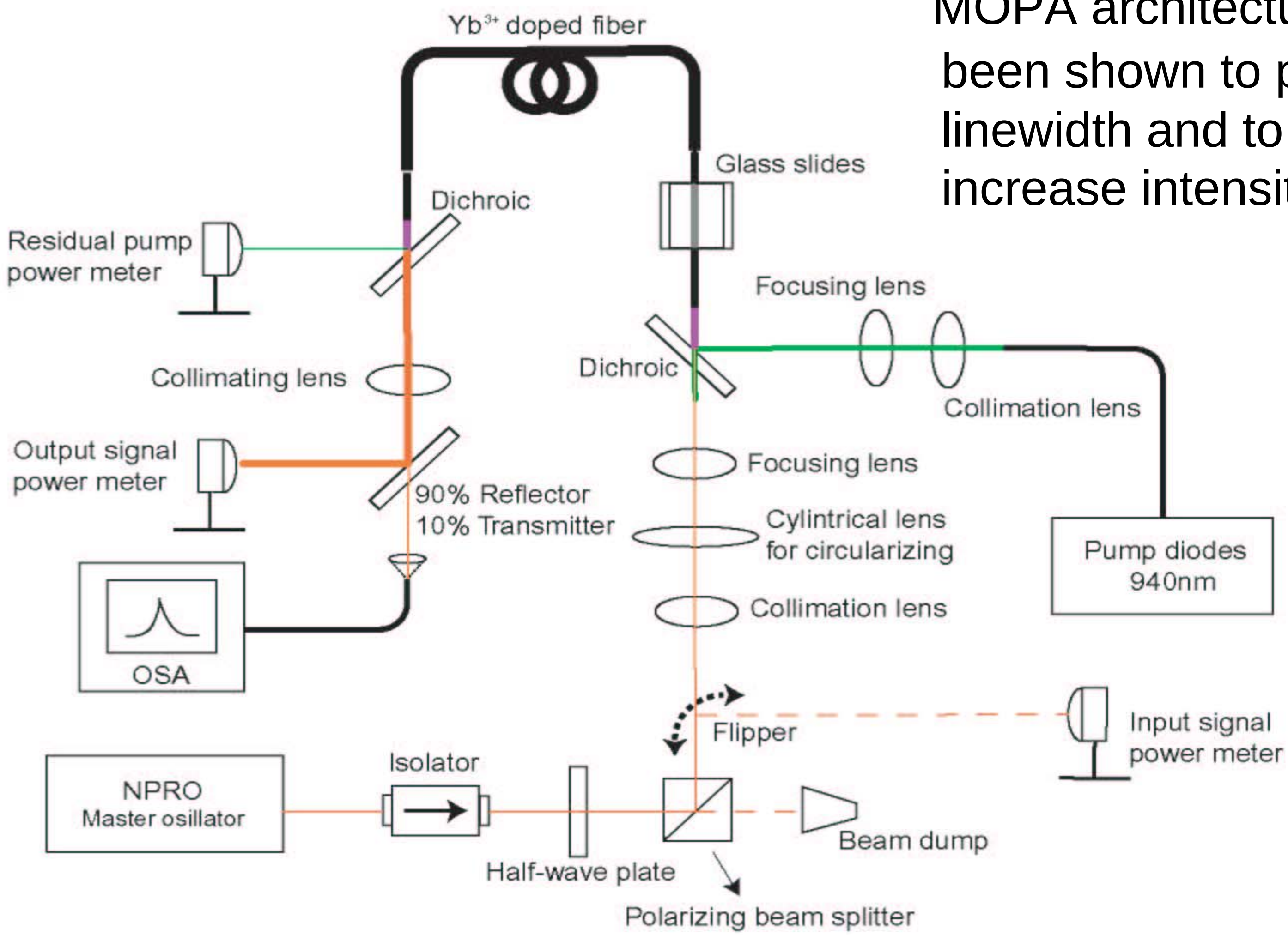
Mueller Gain Matrix

Background loss

* Wagener et al., JLT 1998

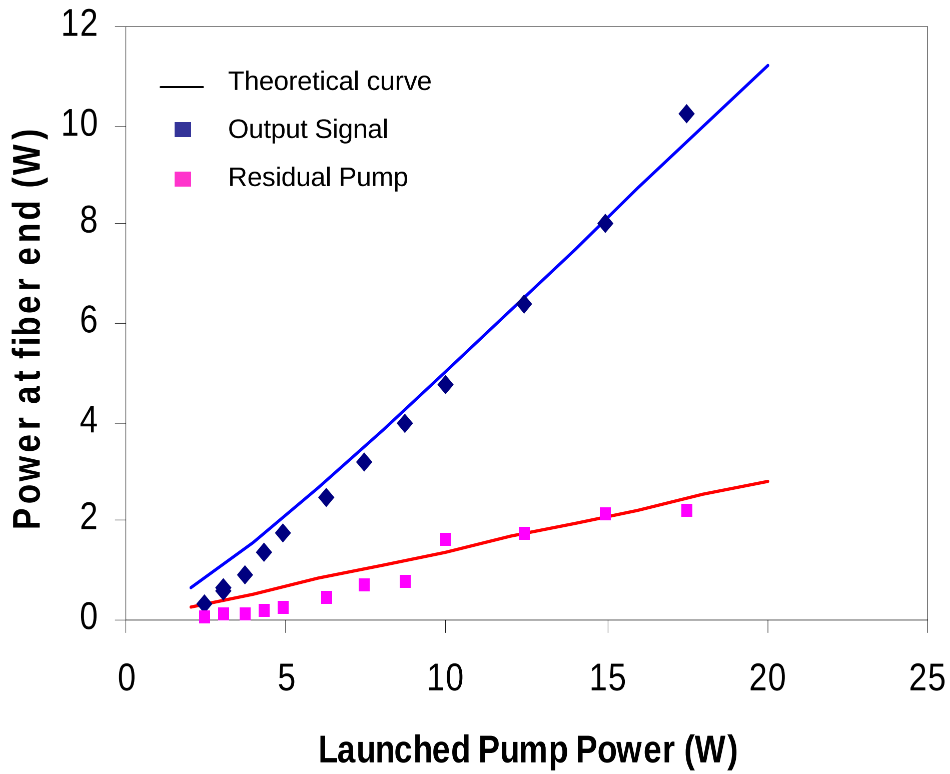
10 W experimental verification

- Experimental set up

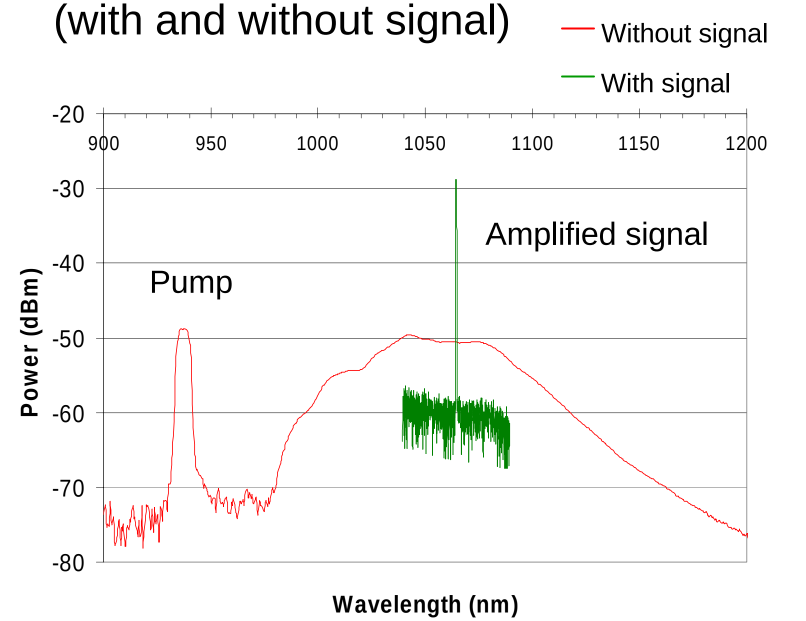


MOPA architecture in fiber has been shown to preserve NPRO linewidth and to not appreciably increase intensity noise

10 W experimental results



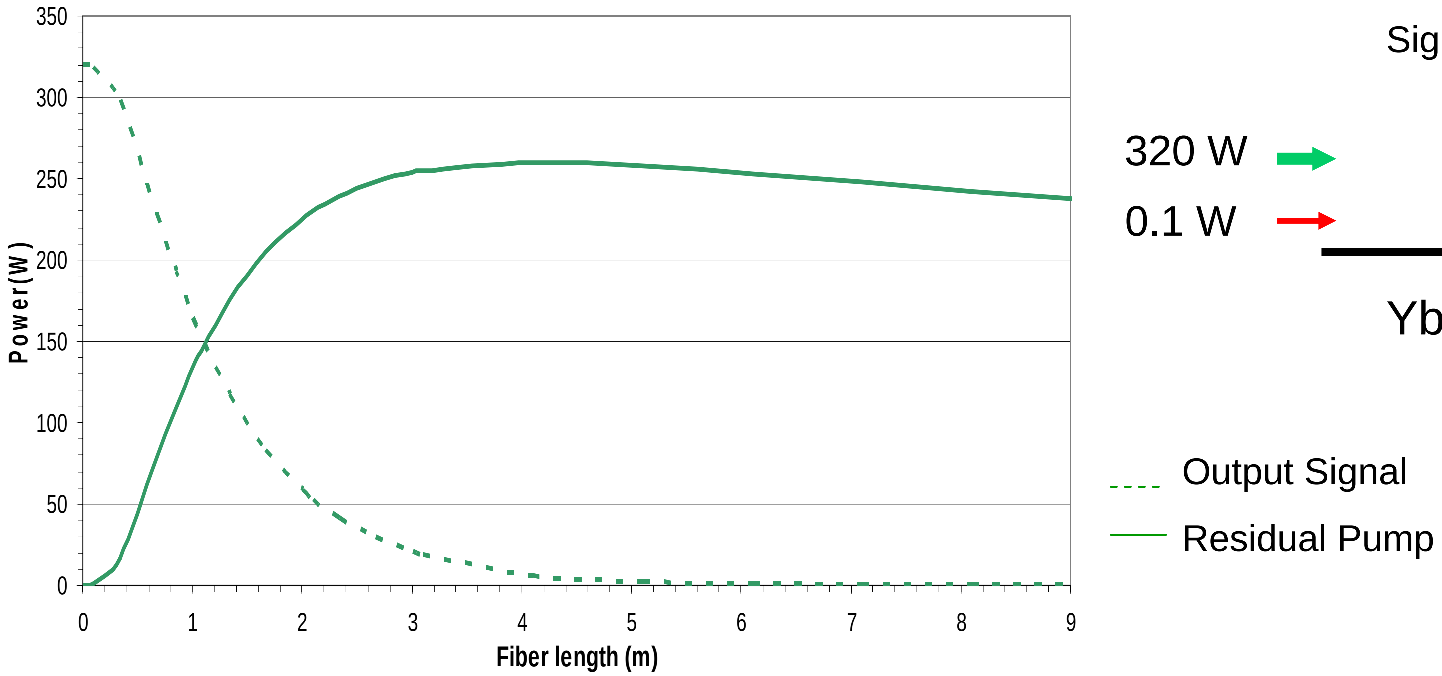
Output spectrum at 3 W launched pump (with and without signal)

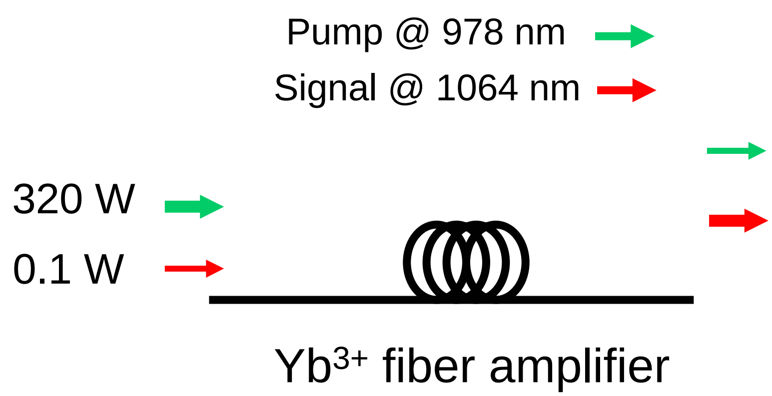


- 10.3 W of output power observed before fiber burned
- 67% optical to optical efficiency with respect to absorbed pump
- Calculated temperature of 59.7ºC at core-cladding interface

250 W simulation (Single Pass Pump)

Power curves
(30 µm core, 250 µm cladding)

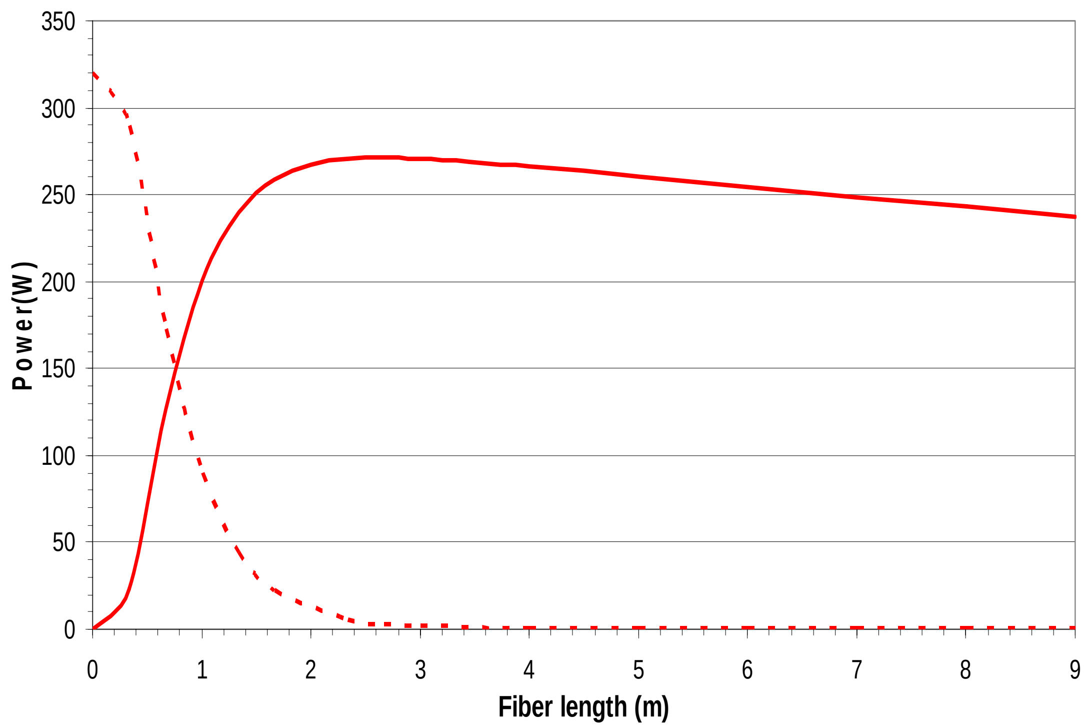


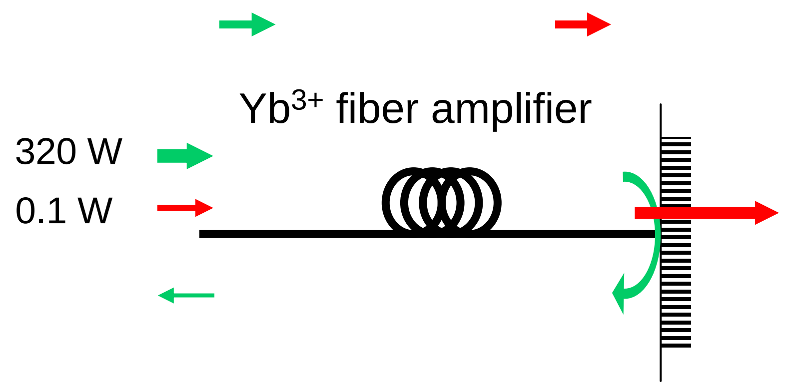


- 250 W of output reached at length of 2.8 meters of commercially available LMA PM fiber (11 dB/m small signal absorption at 978 nm)
- Simulated temperature at core-cladding interface of 127ºC using only natural convection
- Output power meets Advanced LIGO specifications

250 W simulation (Double Pass Pump)

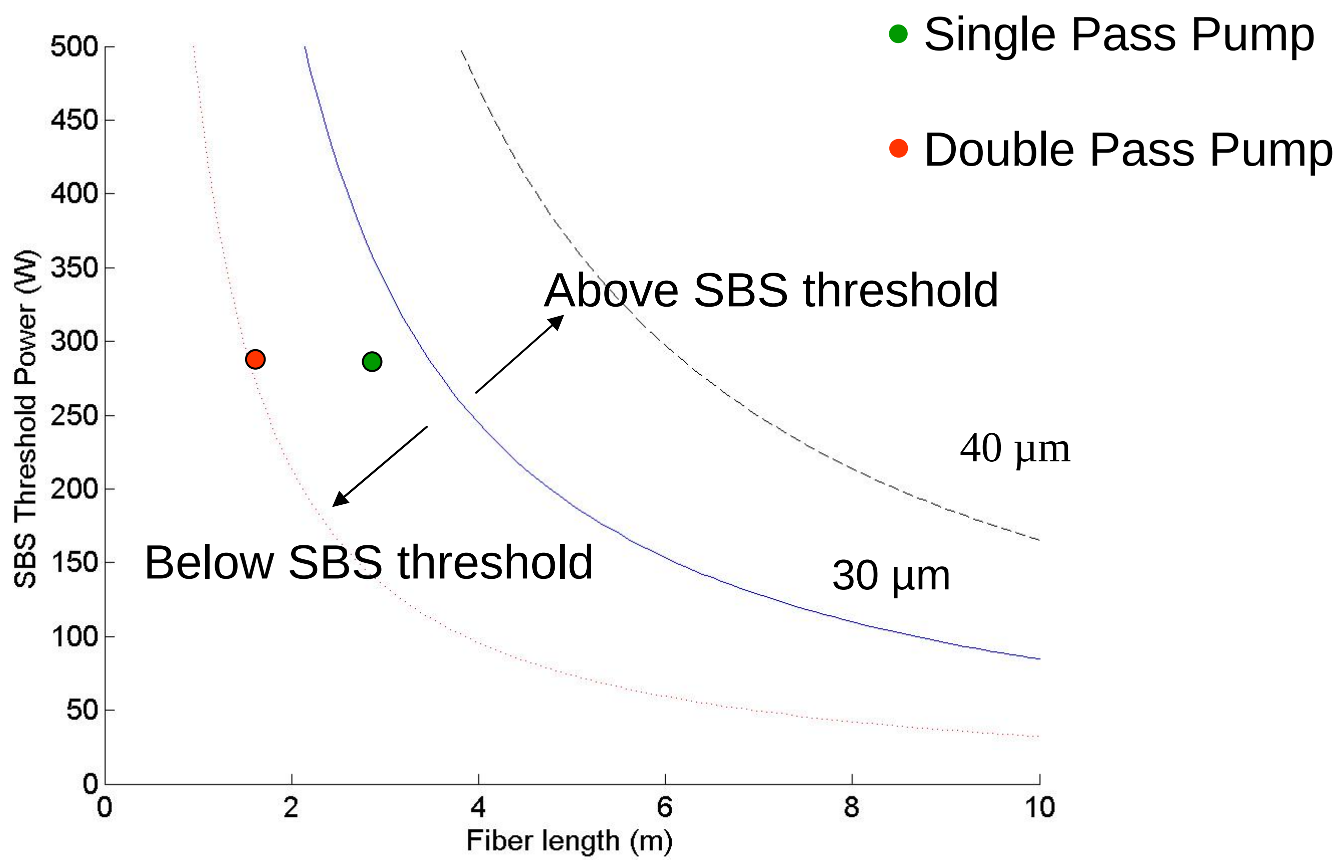
Power curves
(30 µm core, 250 µm cladding)





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

250 W simulation (Nonlinear effects)

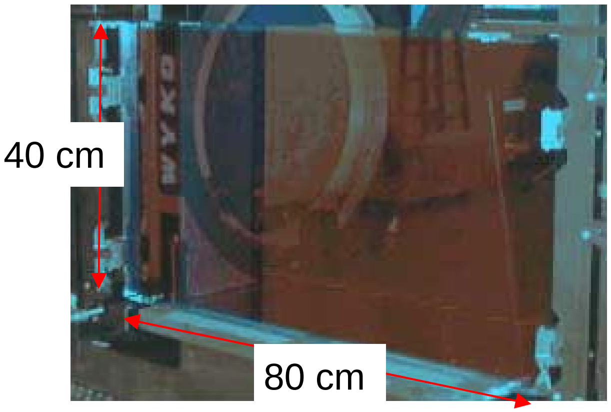


Both single passed pump and double passed pump designs are below the Brillouin threshold for their respective lengths

kW Class Fiber Amplifiers – Phosphates

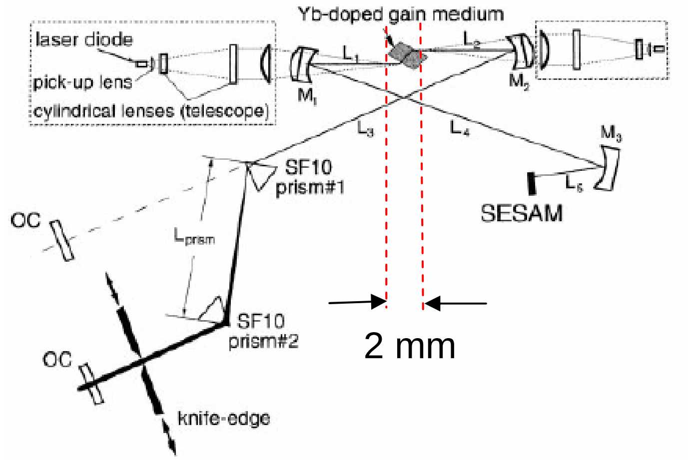
Advantages	Disadvantages
• Can be highly doped (~20 % wt.) without lifetime quenching effects • Shorter lengths avoid nonlinear effects	• Thermal conductivity and thermal shock resistance is not as high as silica • Immature technology compared to silica

Very Large



NIF Nd:Phosphate amplifier slabs

Very Small

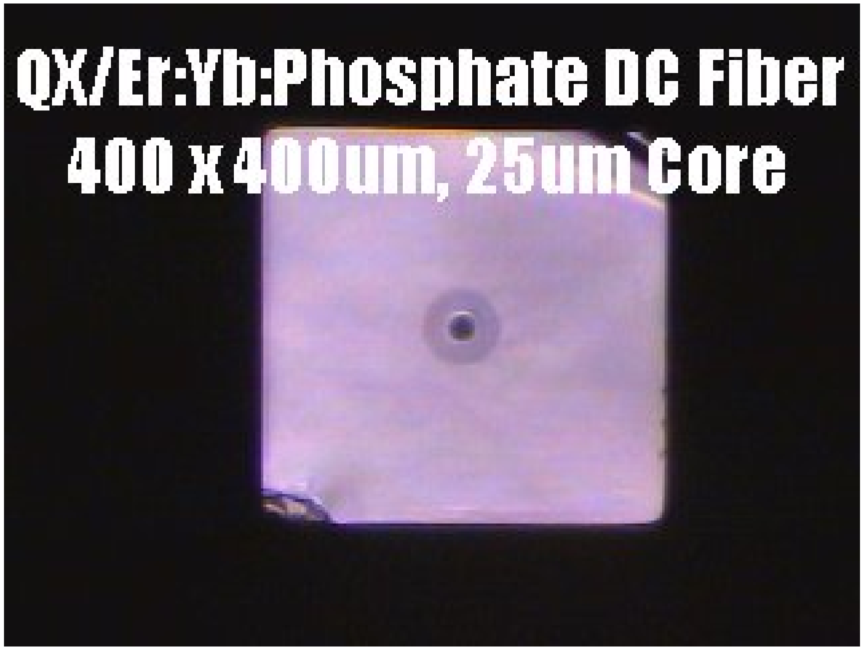


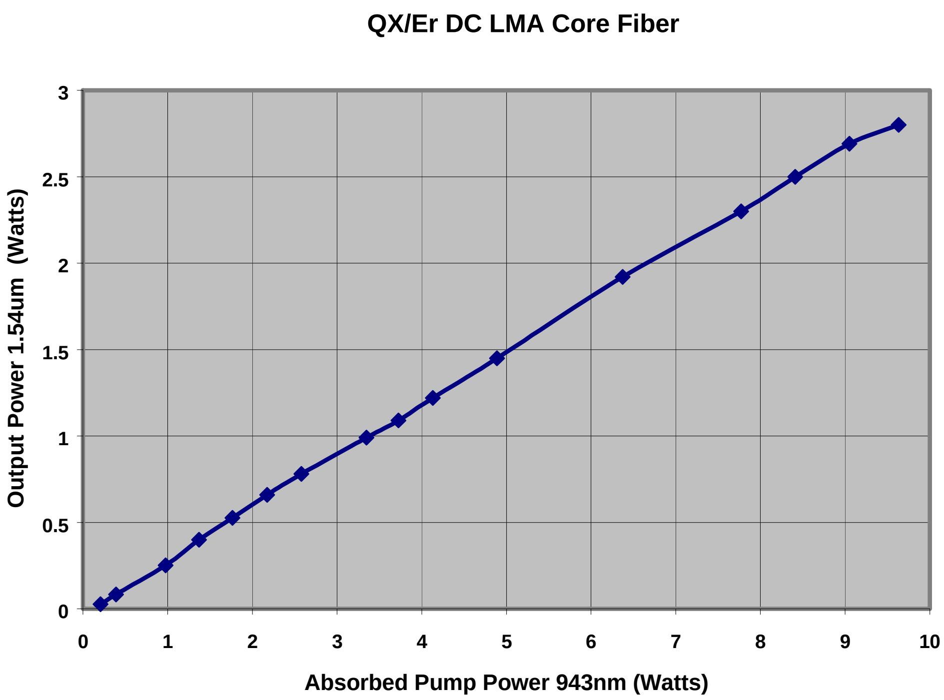
Passively modelocked oscillator

Honninger et al. Appl. Phys. B, 1999

High Power Phosphate Fiber

Recent reported results:

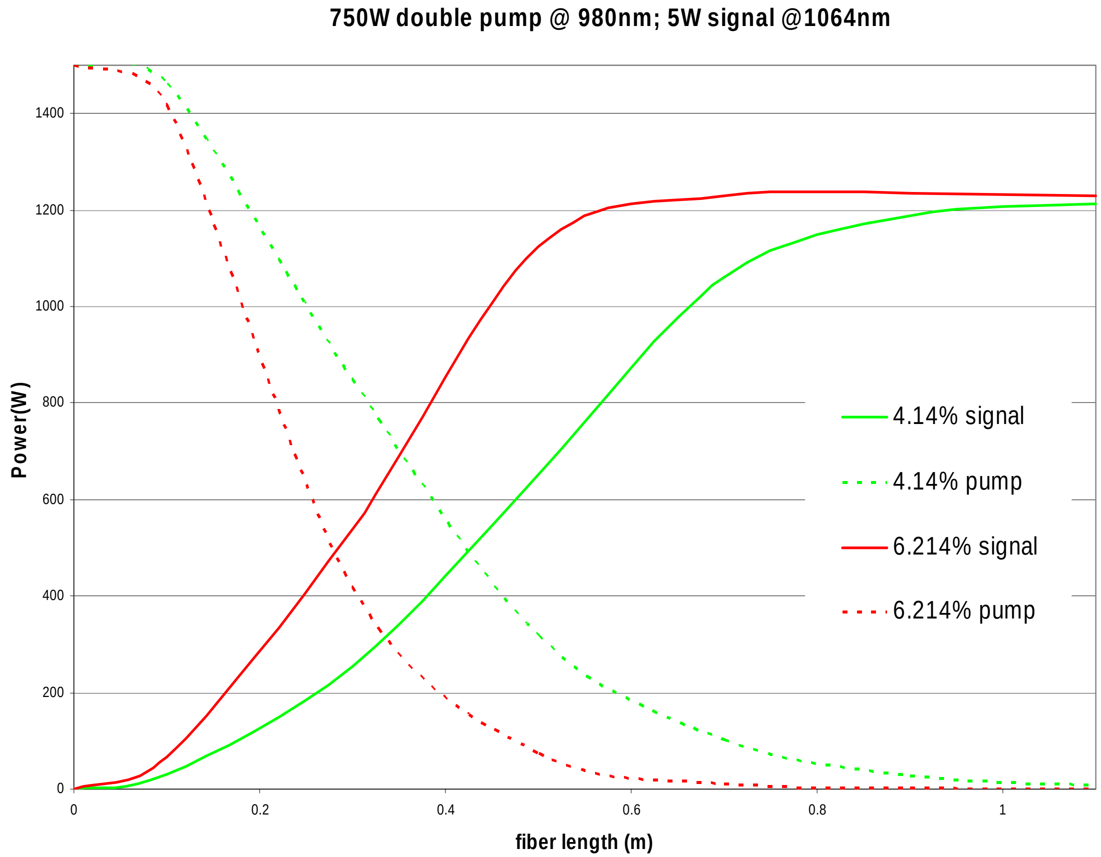


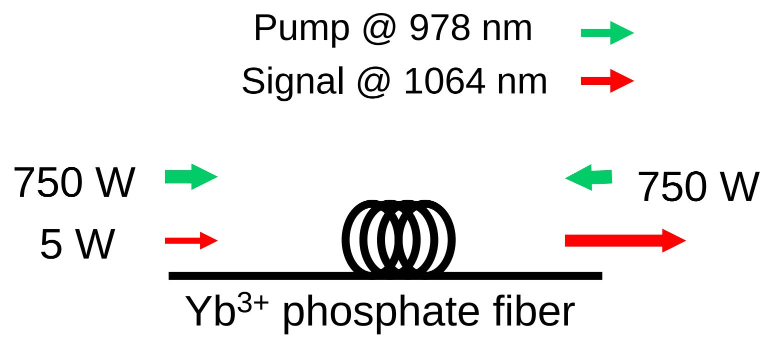


Kigre LMA Double Clad
Erbium-Ytterbium Co-doped
Phosphate Fiber

Myers et al., Photonics West 2003

Kilowatt phosphate simulations





- 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 600ºC

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

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