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

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<th>Advanced LIGO (2007)</th>
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<td>10 W TEM$_{00}$ @ 1.06 µm</td>
<td>165 W TEM$_{00}$ @ 1.06 µm</td>
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<td>Single axial mode</td>
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<td>Laser architecture</td>
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- **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
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
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

LMA Fiber Types

- Standard LMA Fiber
- Holey LMA Fiber

Crystal-Fiber LMA fiber

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*: 

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

* 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

- 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
Above SBS threshold

Below SBS threshold

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

- Can be highly doped (~20 % wt.) without lifetime quenching effects
- Shorter lengths avoid nonlinear effects

### Disadvantages

- Thermal conductivity and thermal shock resistance is not as high as silica
- Immature technology compared to silica

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**Very Large**

NIF Nd:Phosphate amplifier slabs

**Very Small**

Passively modelocked oscillator

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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

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