The Fiber Laser Grand Challenge

Presented to

LDRD Day

Sept. 19, 2007

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LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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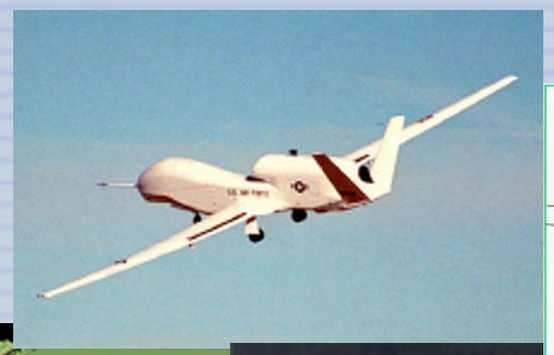
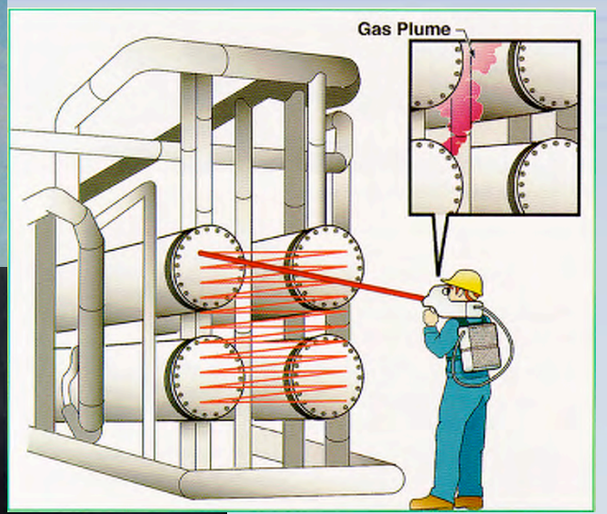
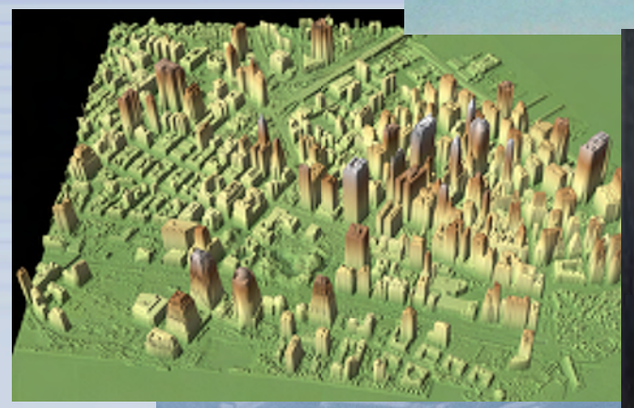
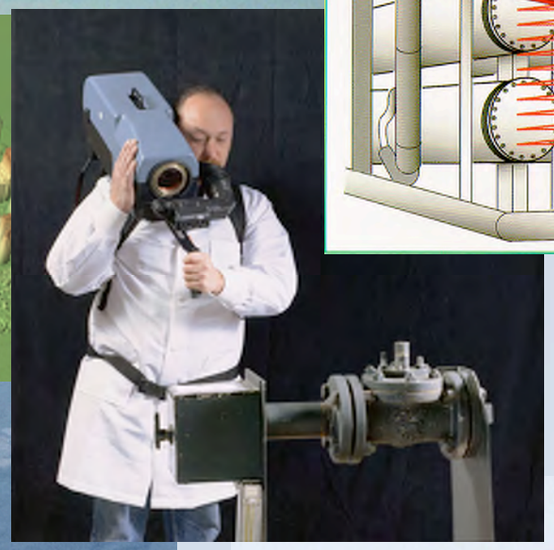
Long-Standing and Emerging National Security Applications for High-Power Lasers

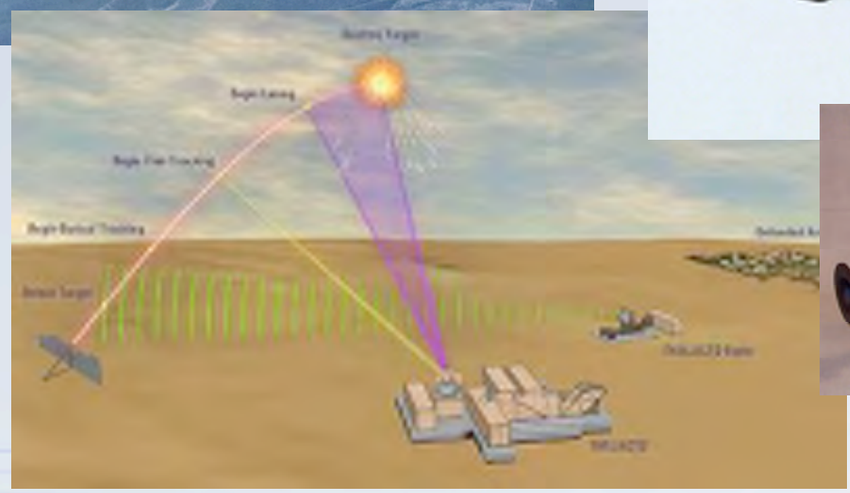
- Remote and *in situ* detection of chem/bio compounds
  - chemical agents
  - biological aerosols
  - WMDs
  - toxic industrial compounds
  - explosives
- Physical sensing
  - ranging / altimetry
  - 3-D ladar
- Secure, free-space, high-speed telecommunications
- Directed energy
  - missile defense
  - IR countermeasures
- Target designation
- Non-lethal weapons

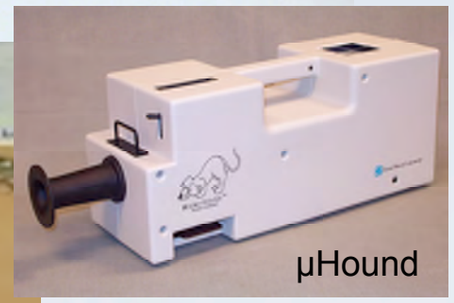












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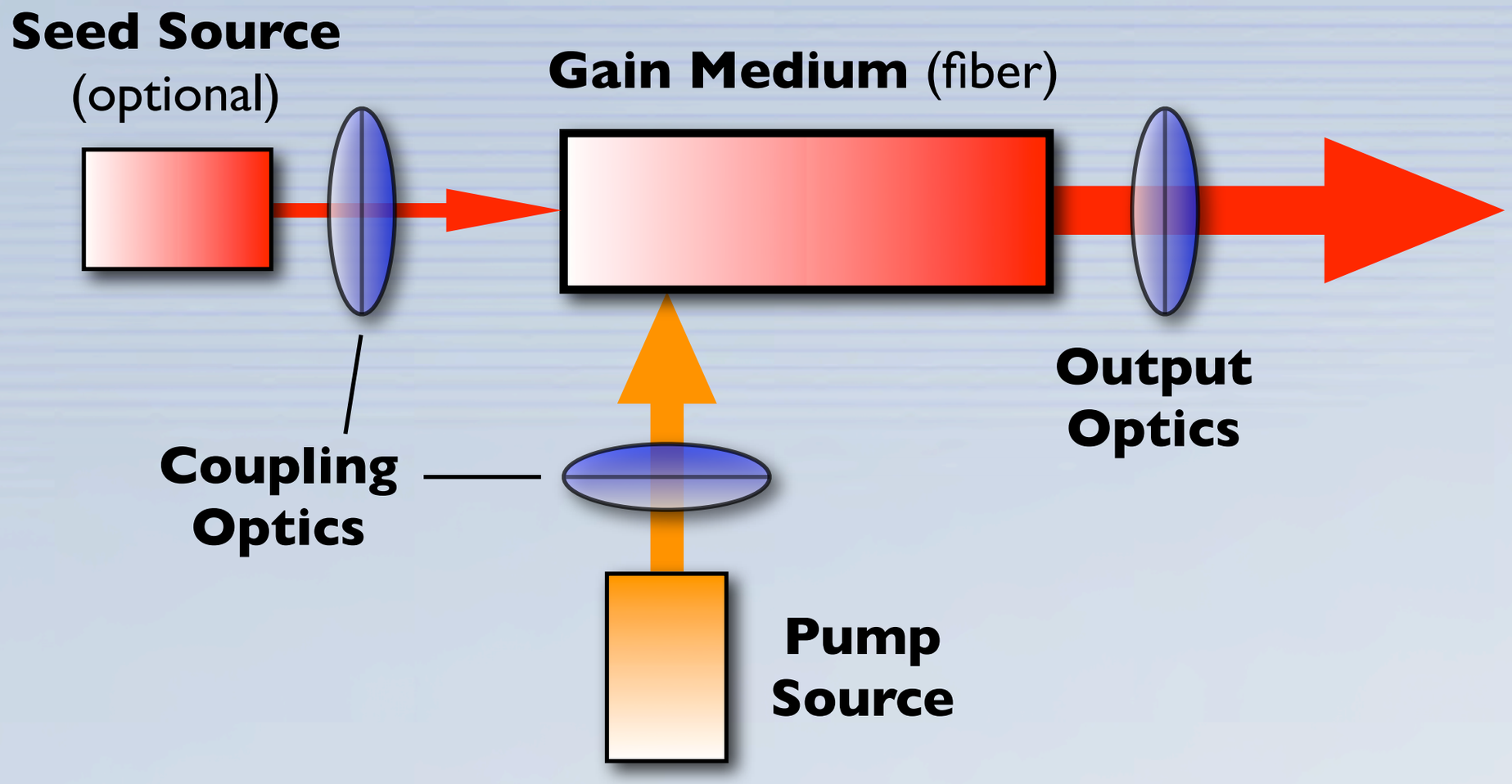
Grand Challenge Approach



- Systematic approach addressing all components and subsystems
- Integrate most optical functions into rugged, monolithic, fiber-optic platform

Grand Challenge Objectives

1. High peak power demonstration

- significant advance beyond current state-of-the art
- reach physical limits of the technology

2. Incorporation of functionality into fiber

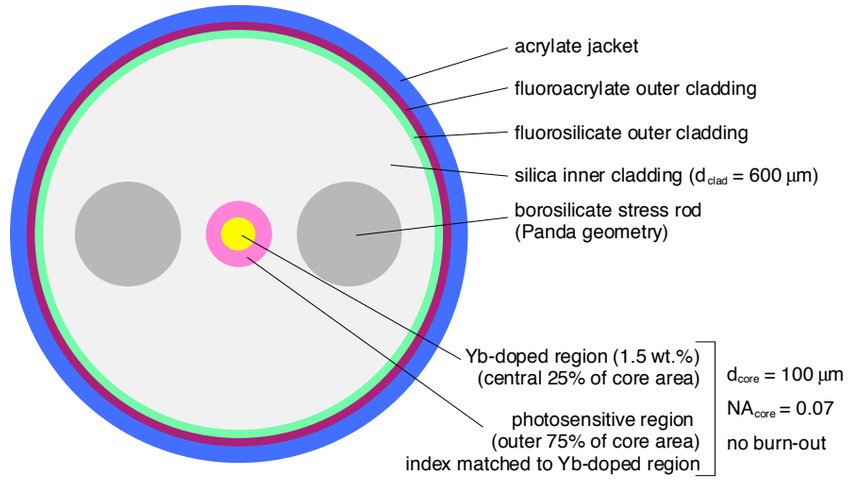
- highly integrated (monolithic) laser systems
- new device designs and system architectures

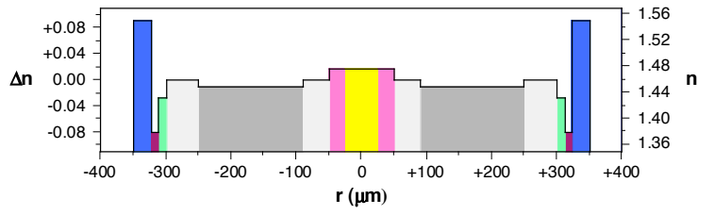
3. Packaged laser system

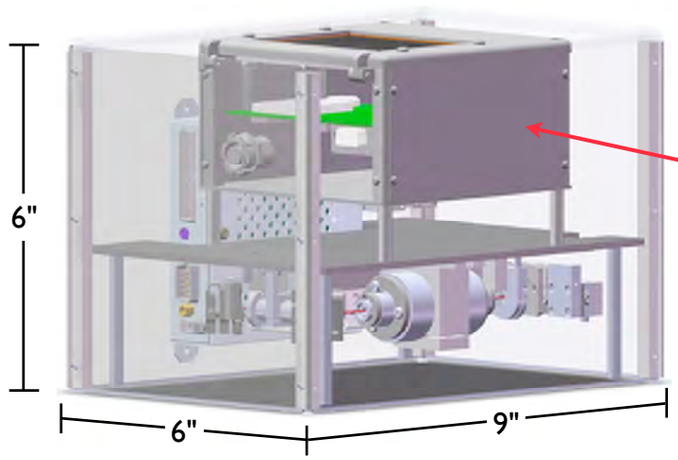
- demonstrate key capabilities
- hardware "deliverable"
- attract customers

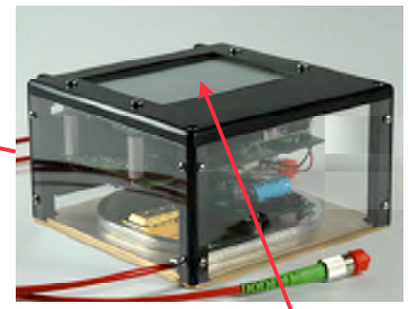
4. Exploratory research

- investigate new concepts
- develop novel capabilities









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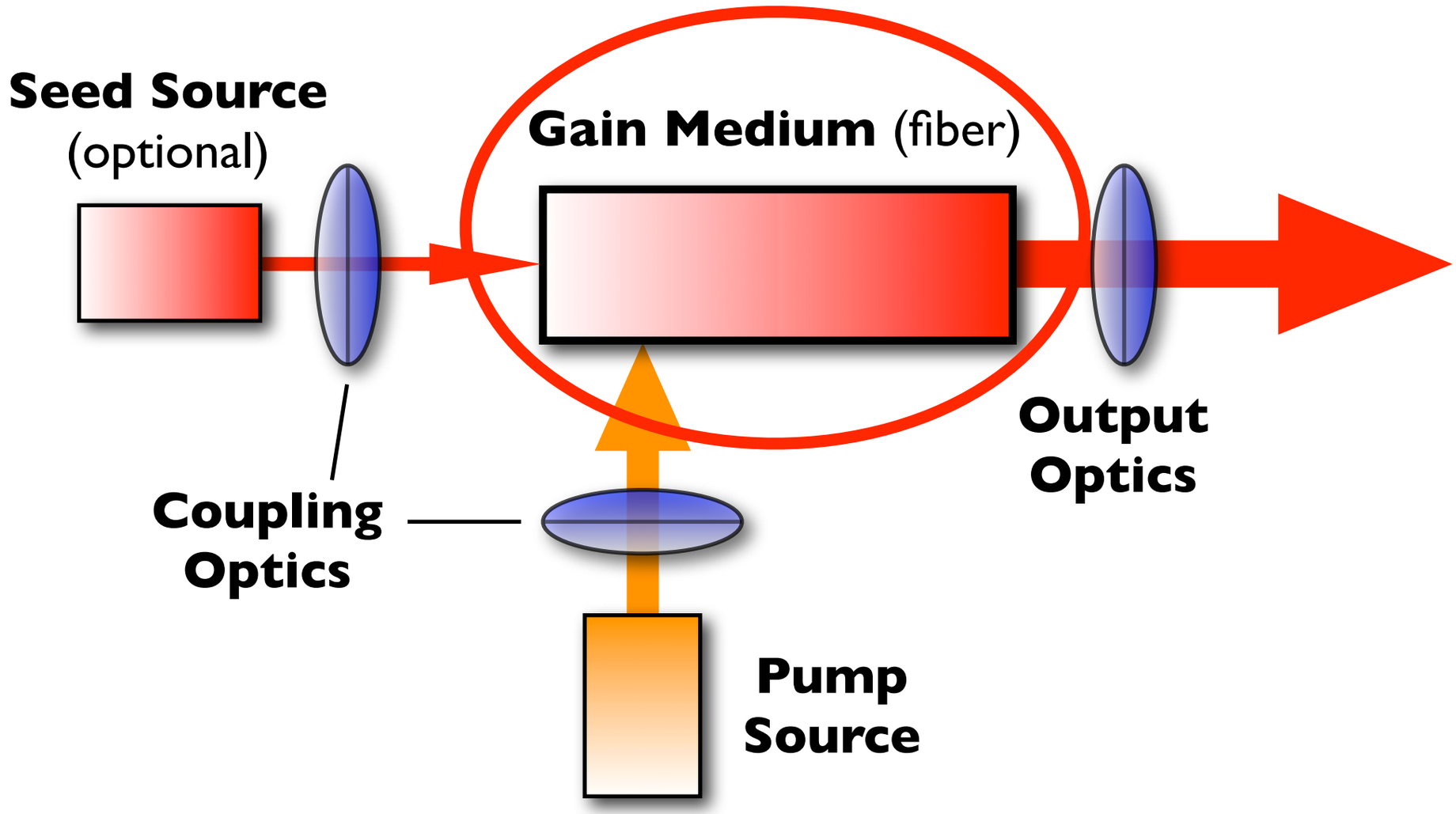
Fiber Gain Medium

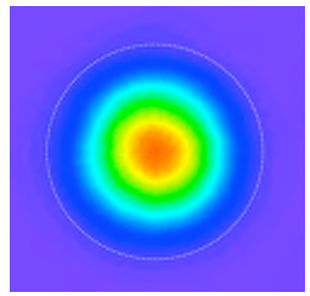


Rare-Earth-Doped Fiber Lasers and Amplifiers

Nd:YAG rod

Yb-doped fiber

Pump and signal beams diffract freely • low gain (~10^1) • low efficiency (~5%)	Pump and signal beams confined by fiber • high gain (~10^5) • high efficiency (up to 40%)
Beam quality determined by cavity design • difficult to achieve diffraction-limited beam quality • beam quality unstable • sensitive to alignment, vibration, temperature, optical power level (thermal lensing)	Beam quality determined by fiber design • single-mode fiber supports only the fundamental mode (LP_{01}) • stable, diffraction-limited beam ($M^2 = 1$)
Low surface-area-to-volume ratio • heat removal difficult • thermal lensing	High surface-area-to-volume ratio • facile thermal management • air cooling
Discrete optical components • free-space beam path • subject to misalignment and contamination	Fiber-coupled components • hermetically sealed, alignment-free optical path • rugged, reliable
Sharp optical transitions • discrete operating wavelengths	Broad optical transitions • wide range of operating wavelengths • continuous tunability



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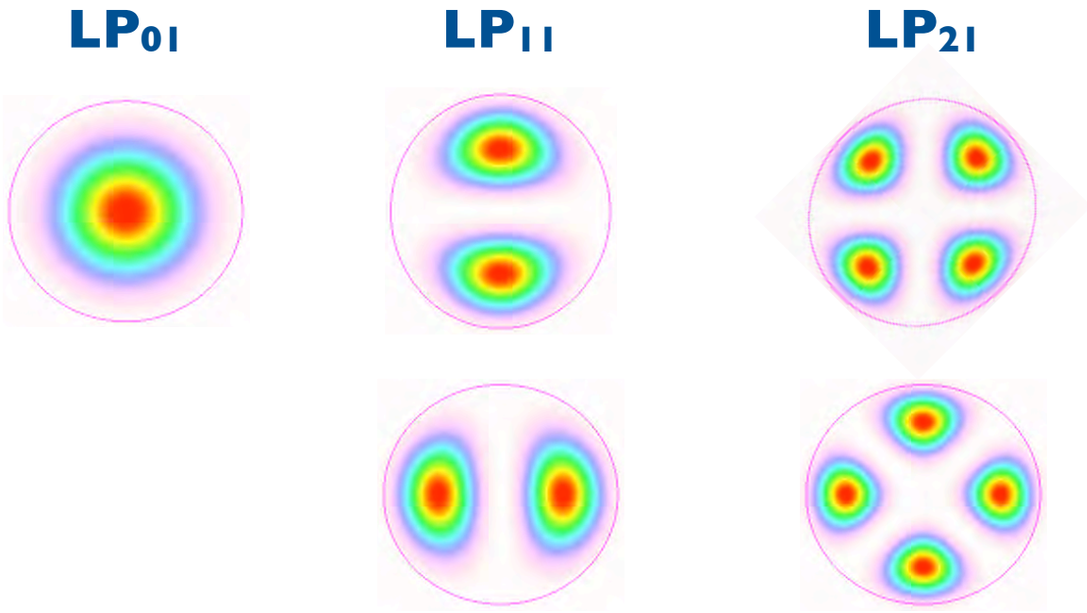
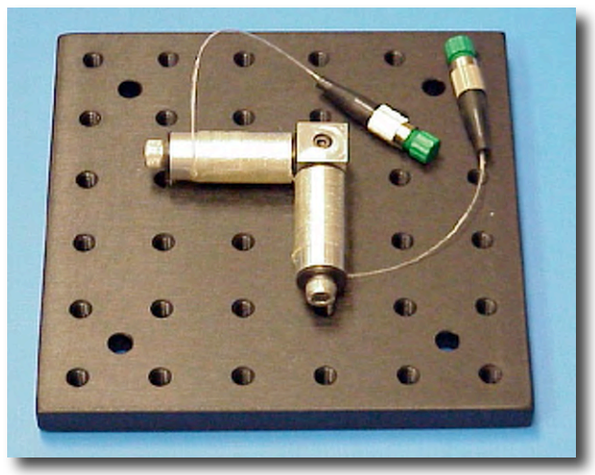
Conventional Fiber Sources are Limited to Low Output Powers

- **low energy storage** (pulsed)
- **onset of nonlinear processes** (cw and pulsed)

Approaches to power scaling:

- large-mode-area, single-mode fiber (low NA, large core)
  - holey fiber
- multimode fiber
  - control of seed launch conditions, cavity configuration
  - customization of refractive-index and dopant profiles
  - **bend-loss-induced mode filtering**





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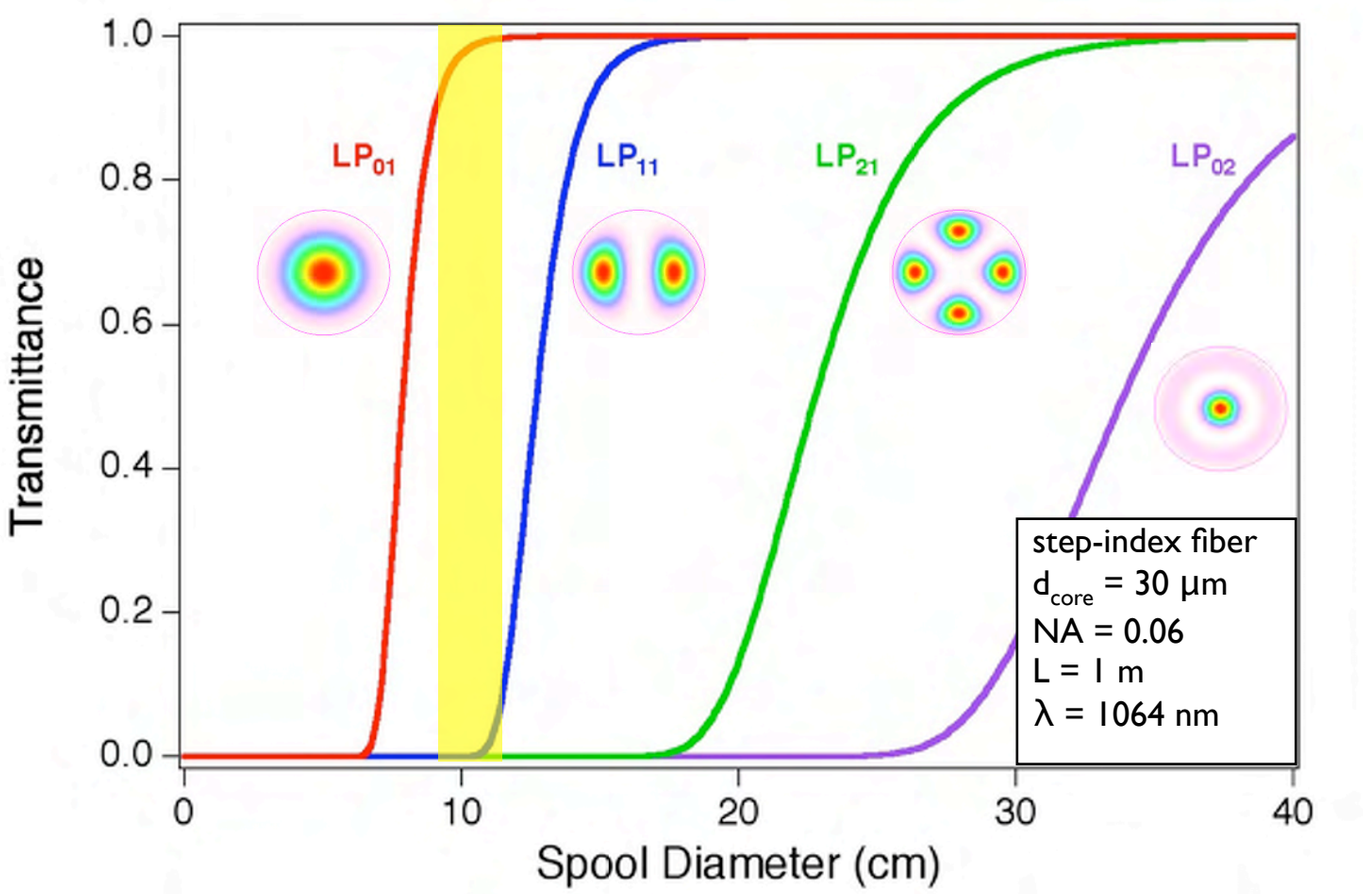
Bend-Loss-Induced Mode Filtering



- distinct from conventional spatial filtering
  - distributed loss along gain fiber
  - power does not build up in high-order modes
  - energy remains in fiber, available to be extracted by LP_{01}
- applicable to many fiber types
- applicable to amplifiers, lasers, and ASE sources
- power scaling of cw and pulsed sources
- fiber ends are unobstructed
- simple, inexpensive

R&D 100

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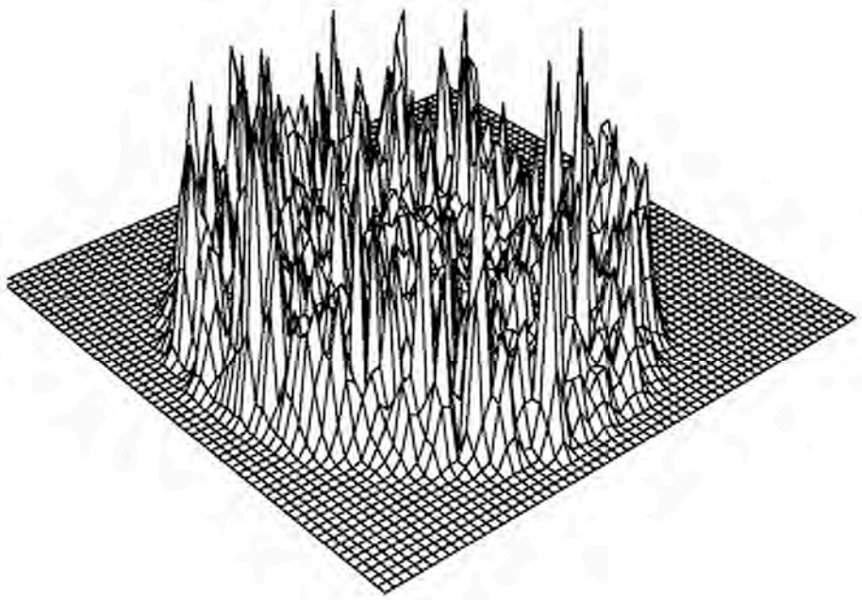
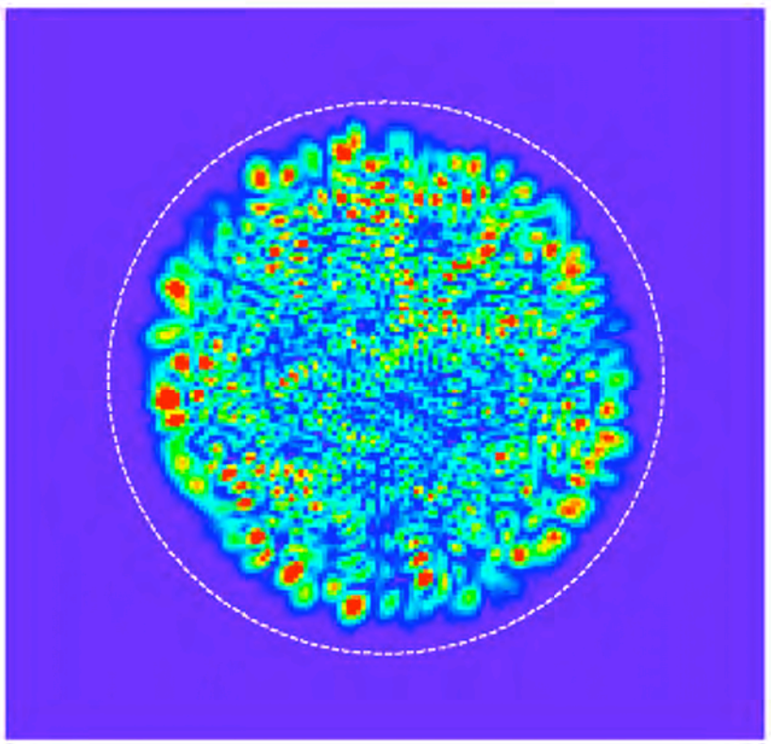
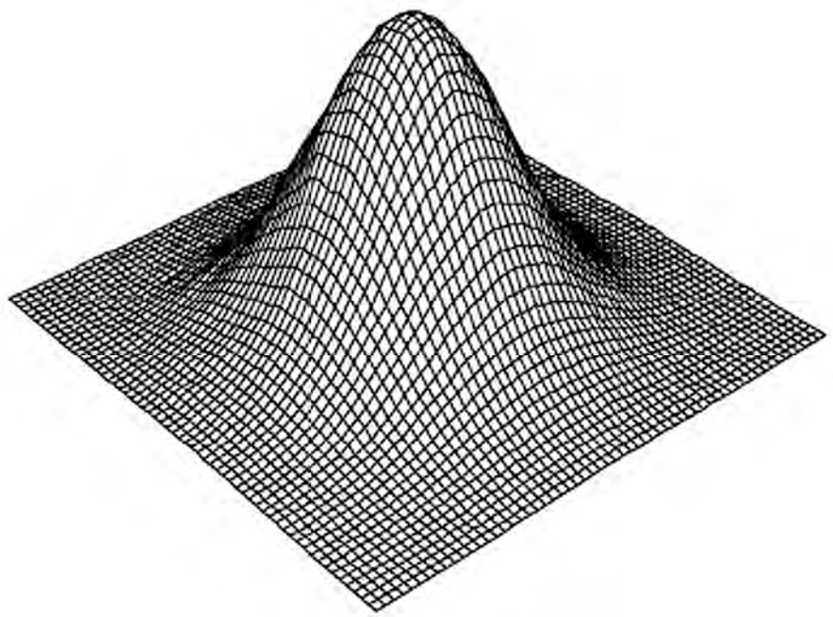
Beam Quality

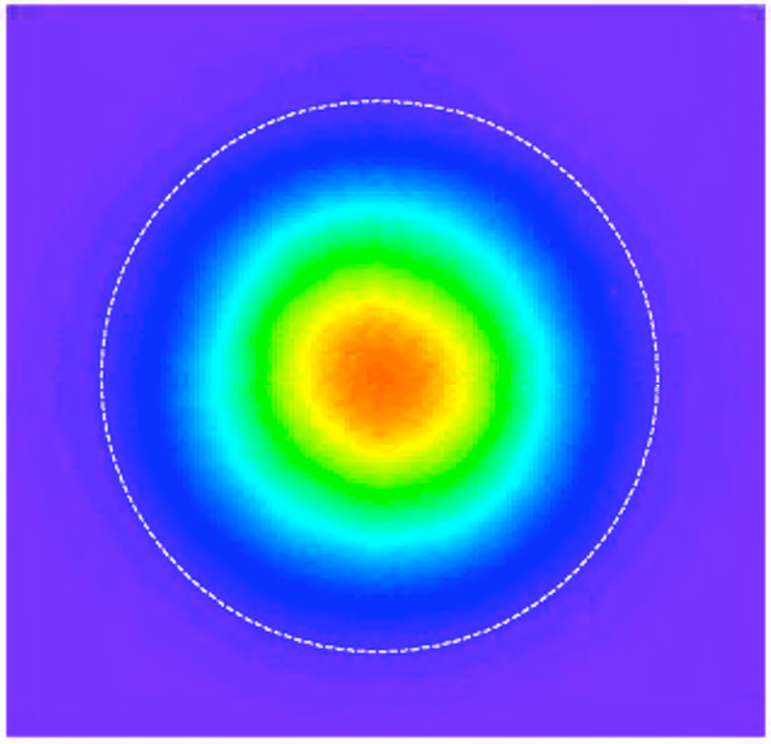
Uncoiled





Coiled





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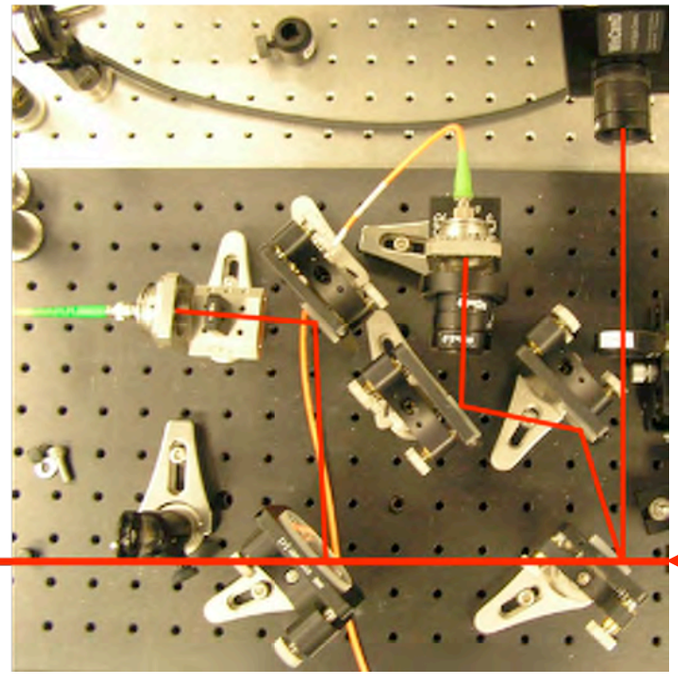
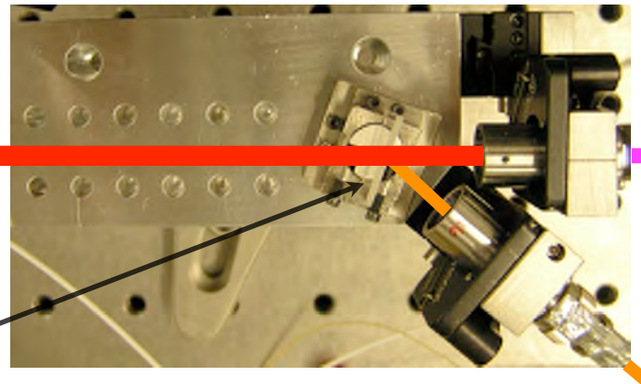
Experimental Setup

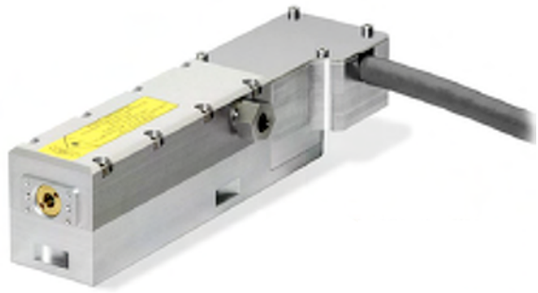
Diagnostics



Fiber Parameter	Nominal Value
core diameter	30 μm
core NA	0.06
index profile	step-index
cladding diameter	250 μm
pump absorption	15 dB/m

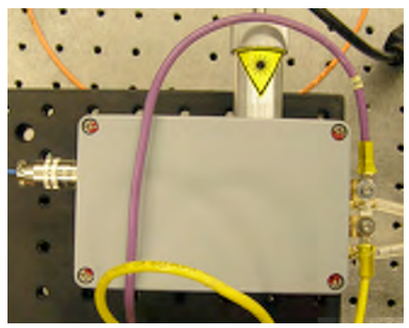


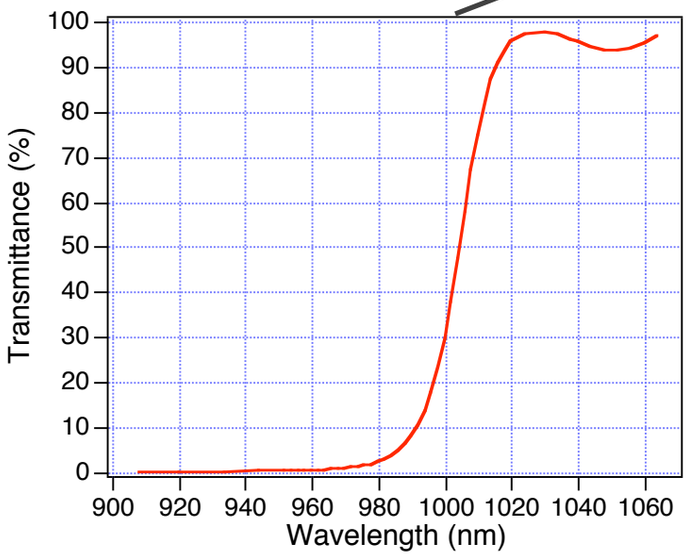
Nd:YAG microchip seed laser

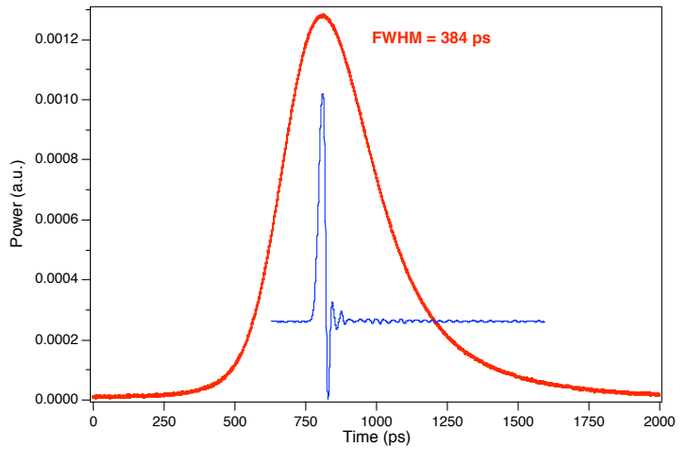


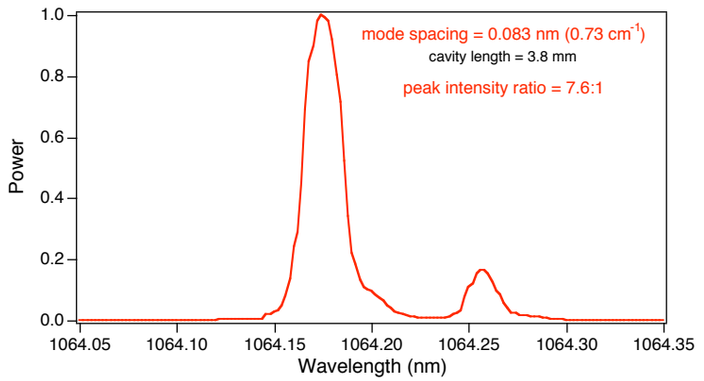
Fiber-coupled pump diode

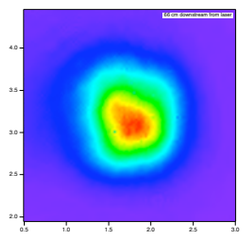
- 200 μm core
- 0.22 NA
- ~976 nm
- 50 W











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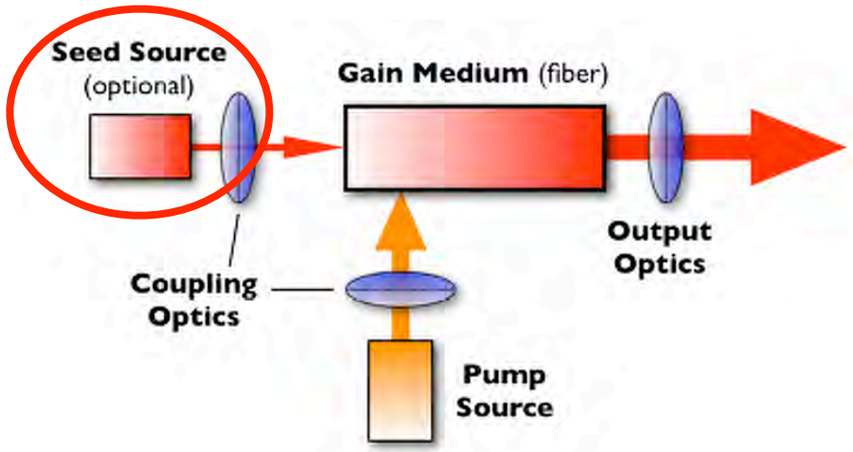
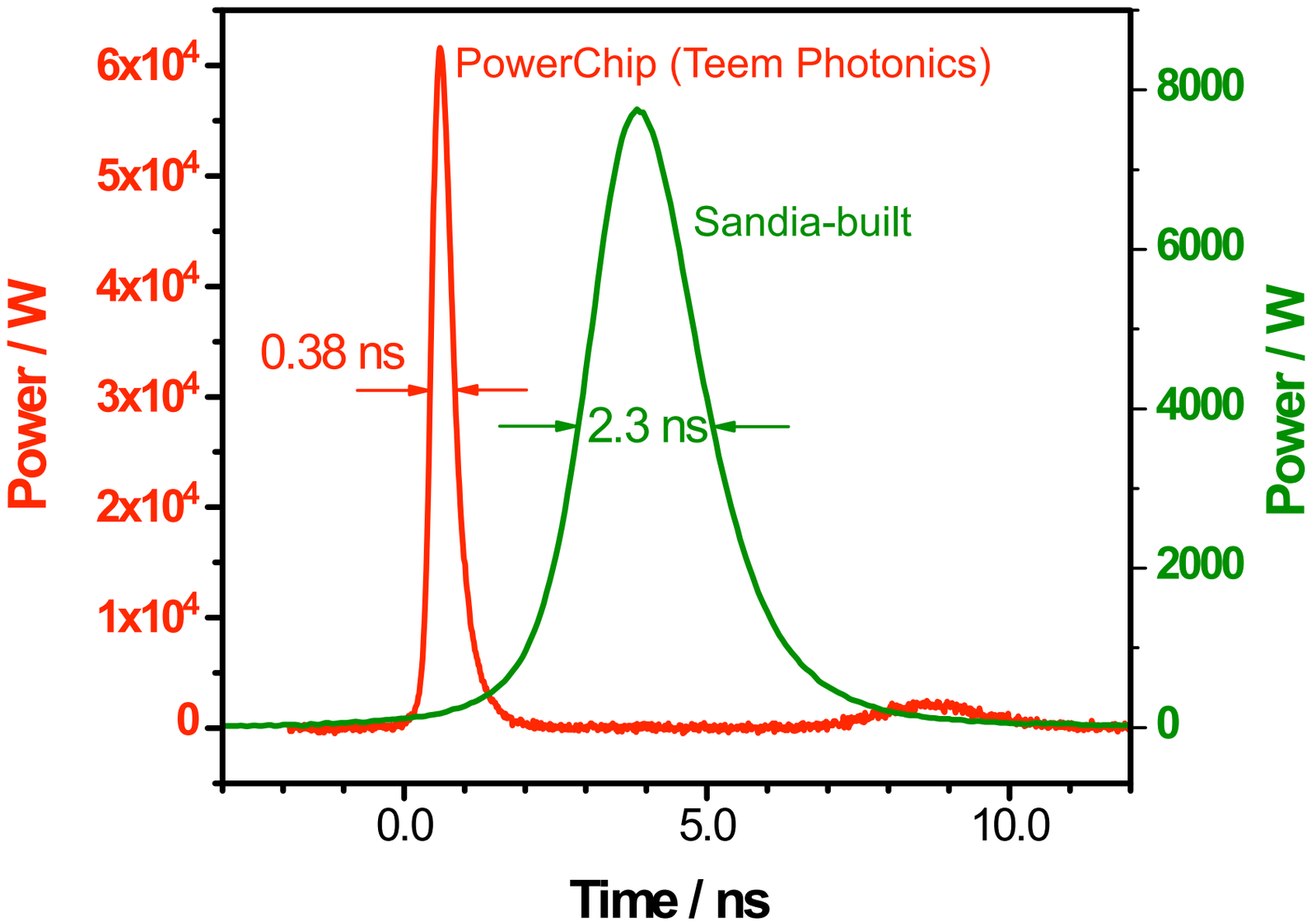
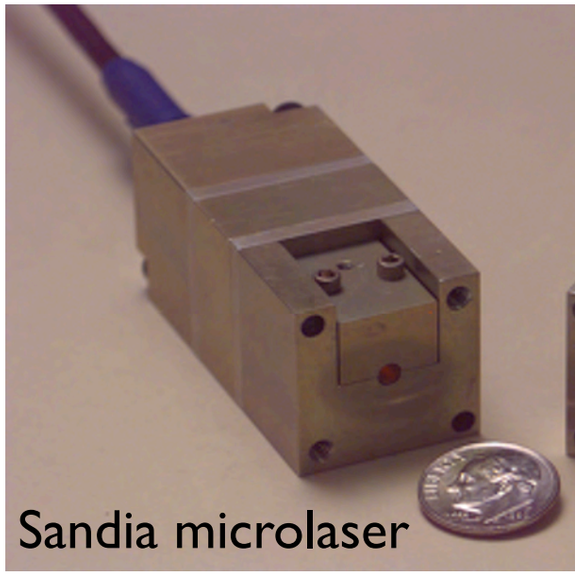
Nd:YAG Microchip Seed Lasers






Sandia microlaser

Wavelength
= 1064 nm

Repetition rate
= 1 kHz

Pulse energies
≤ 35 μJ
≤ 20 μJ

Linewidths
≈ 0.05 cm^{-1}
< 0.02 cm^{-1}

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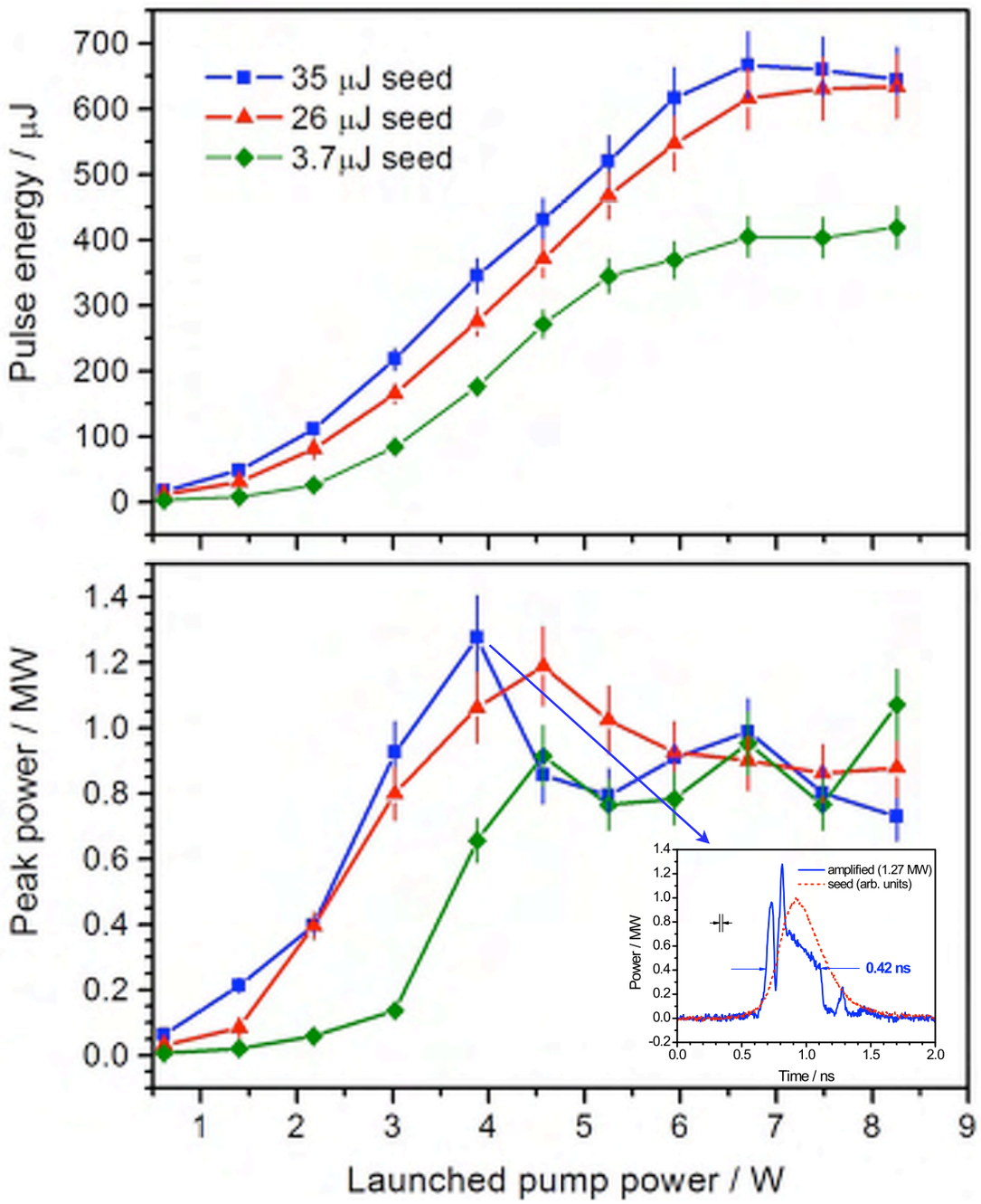
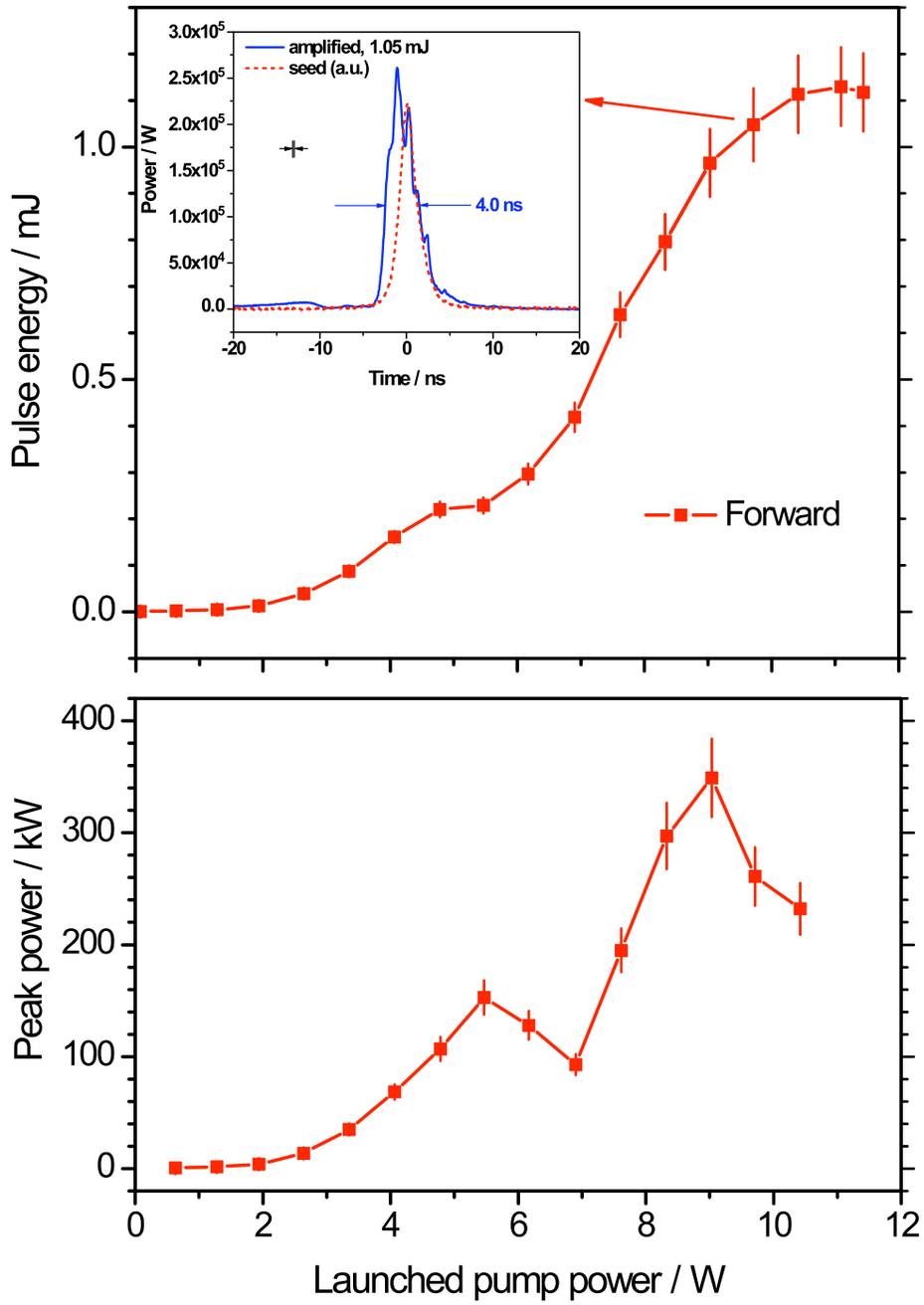
Experimental Results

0.38 ns seed laser



Highest reported peak irradiance: 440 GW/cm^2

2.3 ns seed laser



Highest reported peak fluence: 410 J/cm^2

Consistent with recent preform damage-threshold measurements

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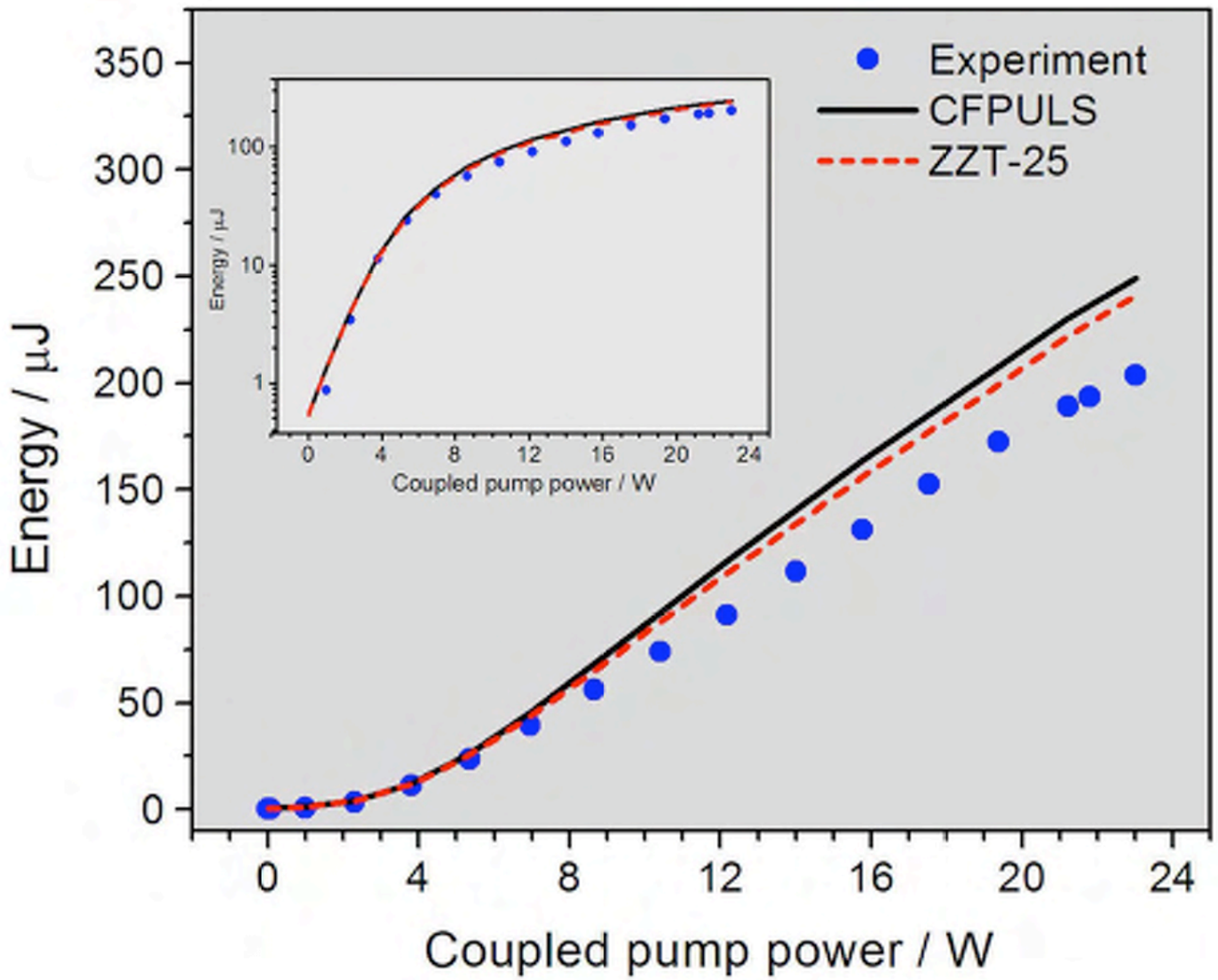
Pulsed-Amplifier Modeling

- 3-D, time-dependent models
- Initial inversion profile from multiple-pulse model
  - simplified two-level rate equations
  - includes ASE
  - spectrally resolved
- Transient BPM model
  - includes GVD, SPM, and saturable gain
  - employs measured or calculated bend loss
  - can treat arbitrary index and rare-earth-dopant distributions, varying bend radius, and high-order modes
  - fully predictive, no adjustable parameters



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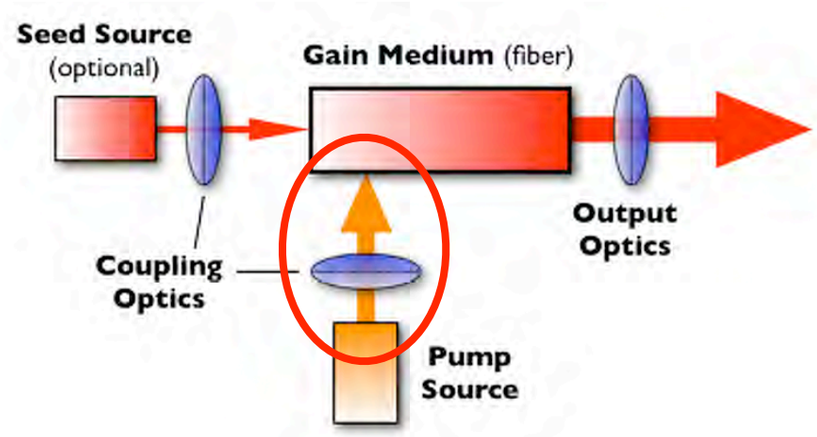
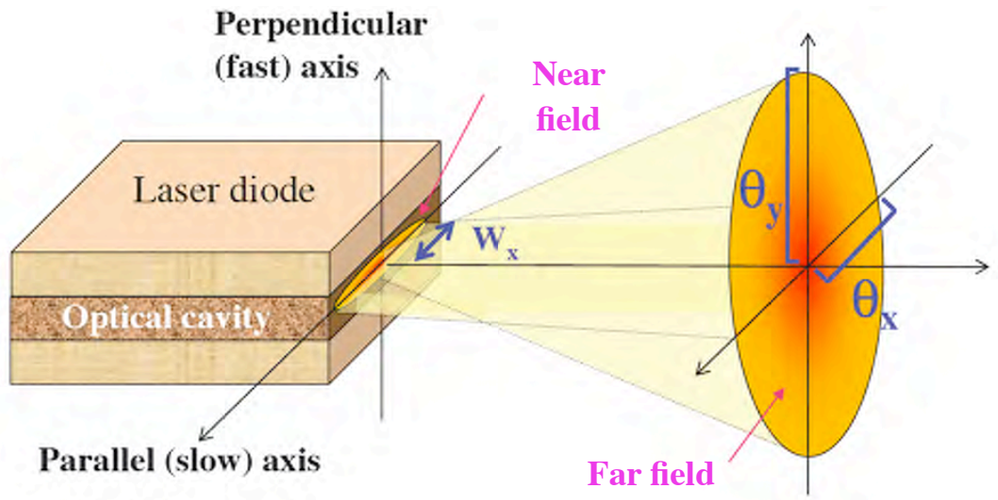
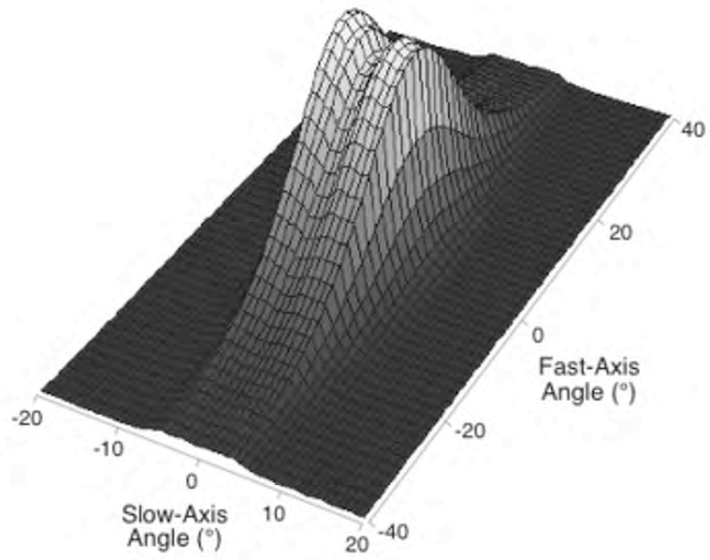
Pumping of Double-Clad Fiber Sources

- Diode pump sources are poorly formatted for coupling into double-clad fiber
  - astigmatic
  - highly divergent
- Evaluation criteria for pumping method
  - coupling efficiency
  - stability
  - alignment sensitivity
  - compactness
  - simplicity
  - scalability
  - conservation of brightness
  - loss for signal (core) light
  - obstruction of fiber ends
  - compatibility with inner-cladding designs
  - compatibility with various pump sources
  - cost







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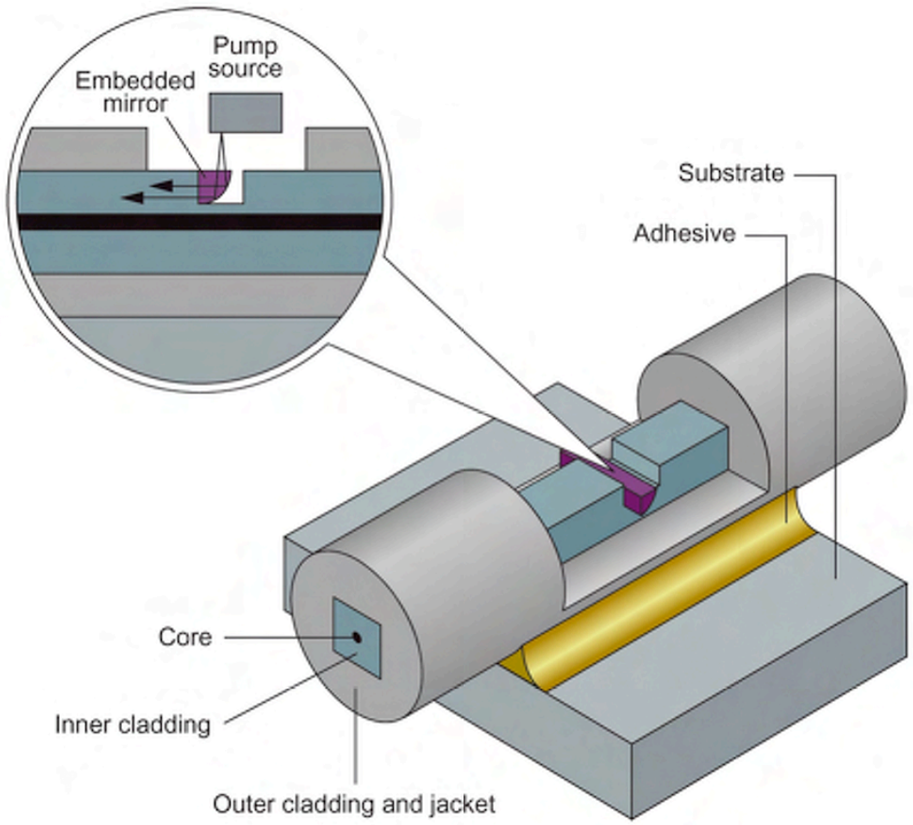
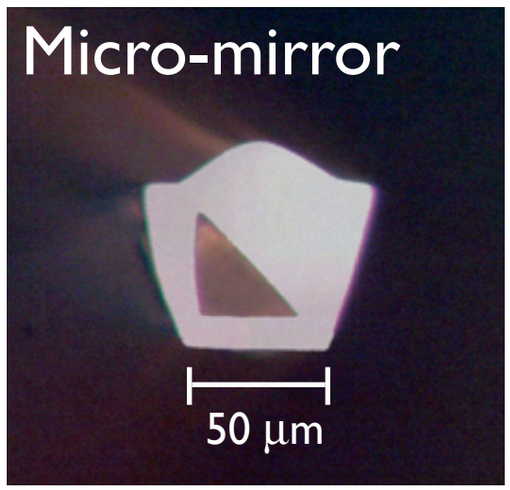
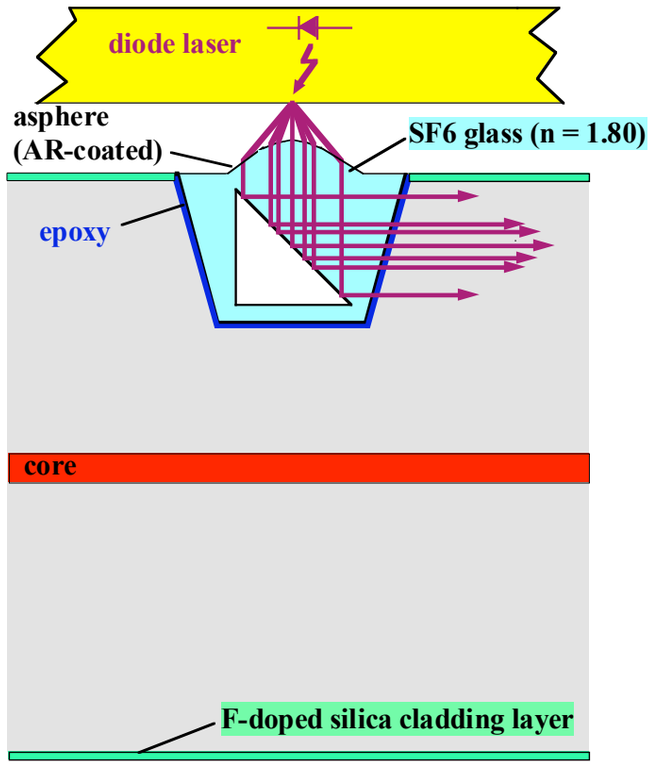
Embedded-Mirror Side Pumping (EMSP)







- efficiency coupling (> 80%)
- low alignment sensitivity
- compatible with a variety of fiber types and pump sources
- scalable
- low parts count
- fiber ends unobstructed
- no loss for light propagating in core
- mirror reduces divergence of pump beam
- compact and rugged
- low cost

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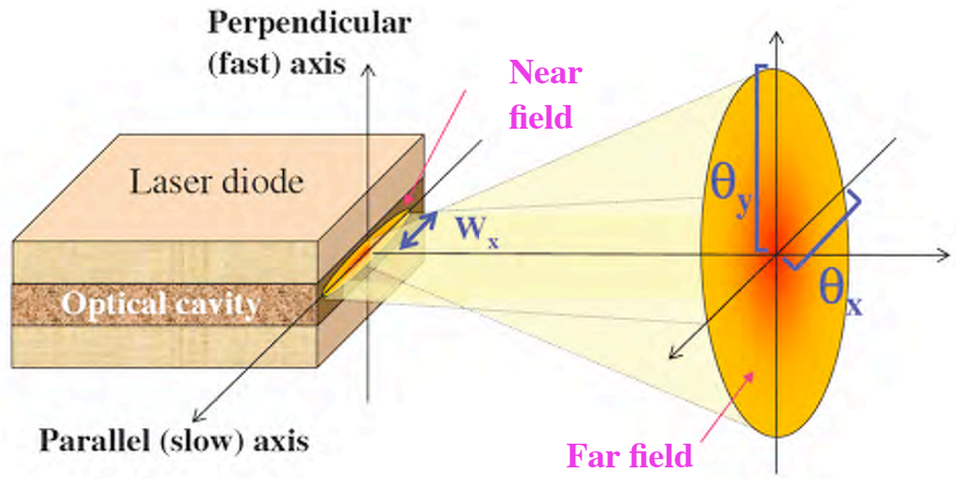
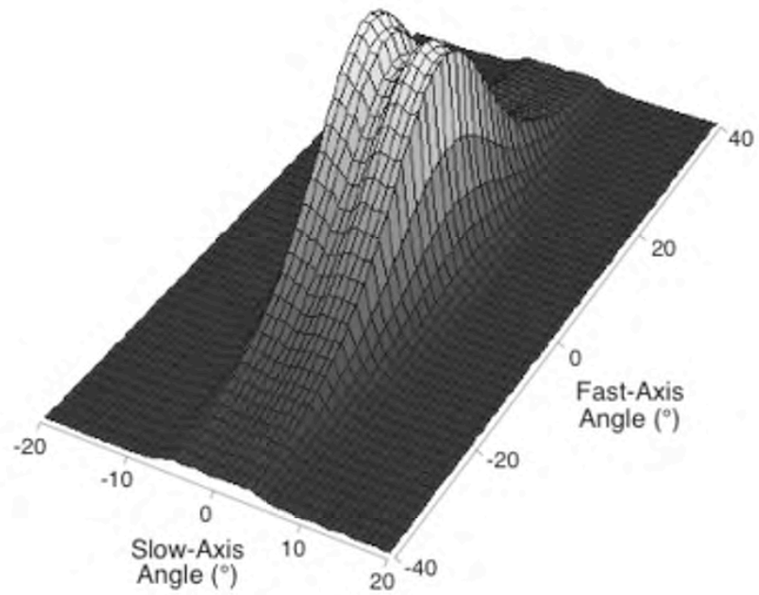
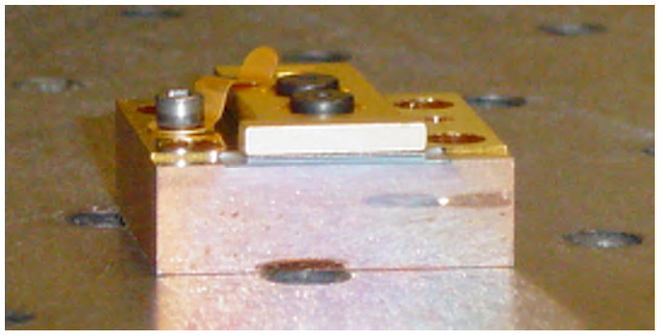
Diode-Bar Pump Sources

Single emitter:





Diode bar:



- most cost-effective source of high pump power
- < $25 / W
- 100 W diode bars commercially available
- poorly formatted for launching into fiber

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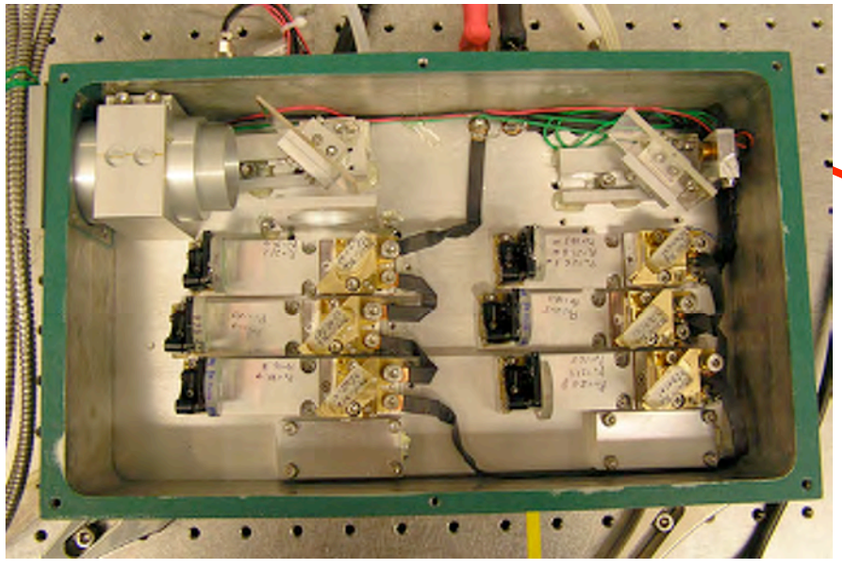
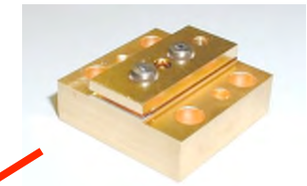
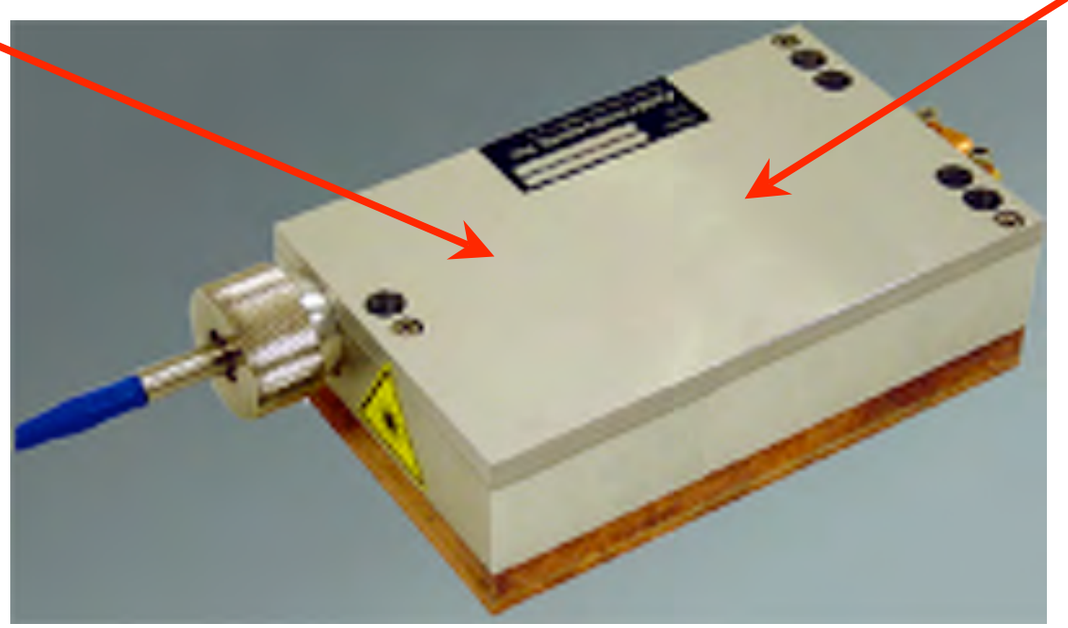
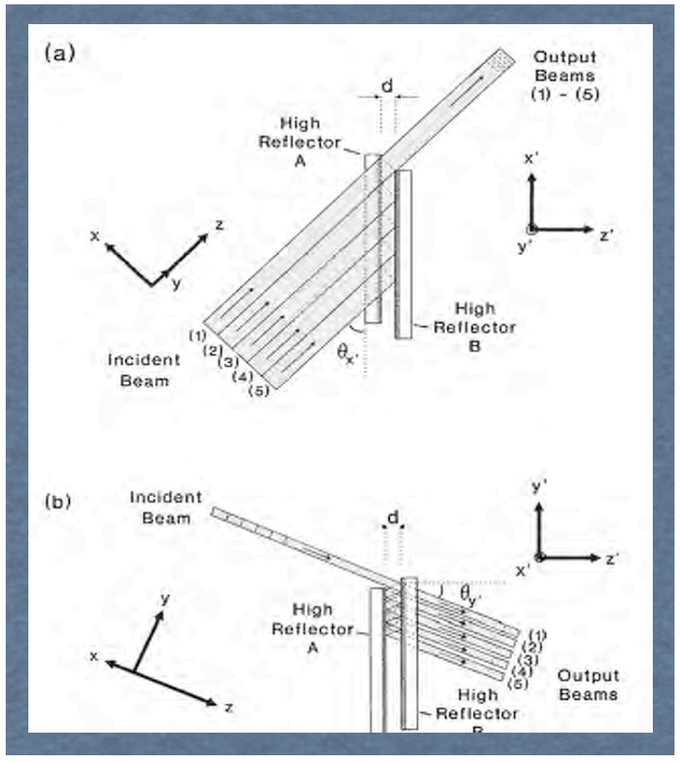
Conventional Approach: Fiber-Coupled Diode Bars









- most common source of high pump power
- significantly more complex, less efficient, larger, and more expensive than raw diode bars
- > $100 / W
- brightness / efficiency tradeoff
- typical net launching efficiency ~50–60% into double-clad fiber

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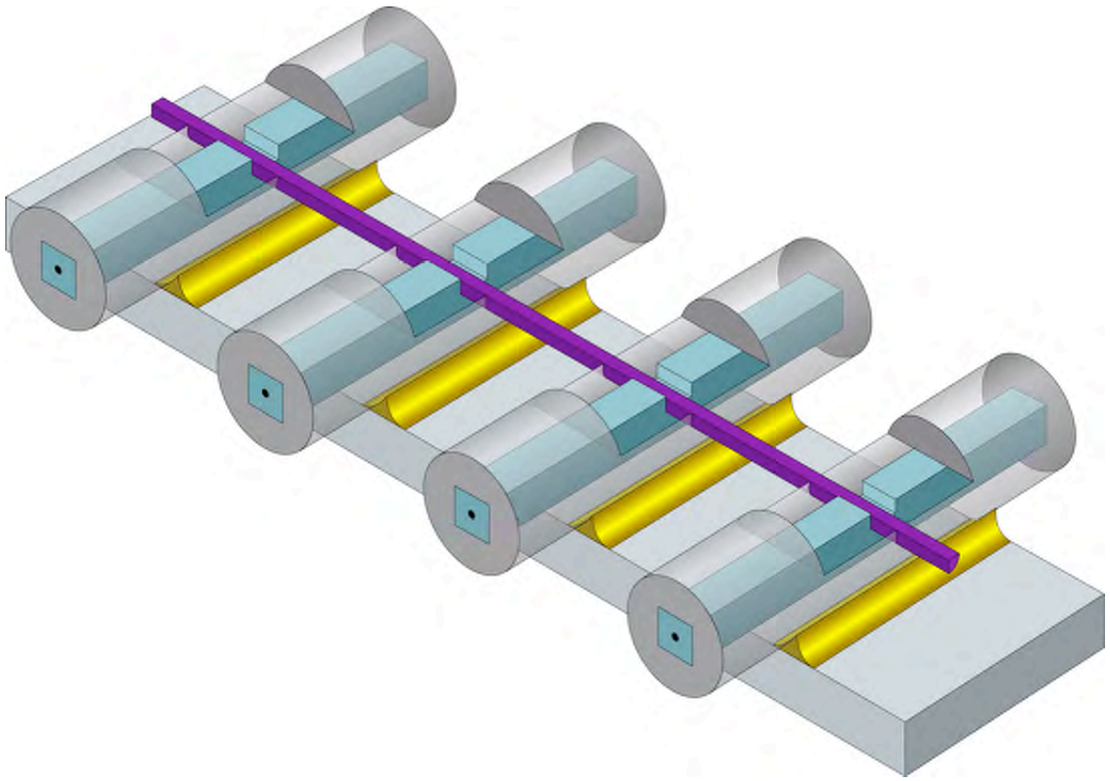
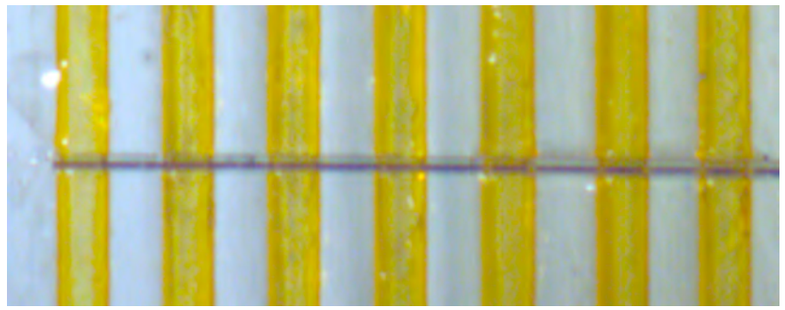
EMSP Direct Diode-Bar Pumping





Proof-of-concept experiments

- 10-emitter diode bar
  - 80 µm stripe width
  - 1.0 mm pitch
- double-clad fiber with 300 µm inner cladding
  - glass-clad (0.22 NA)
  - “dummy” fiber and Yb-doped fiber

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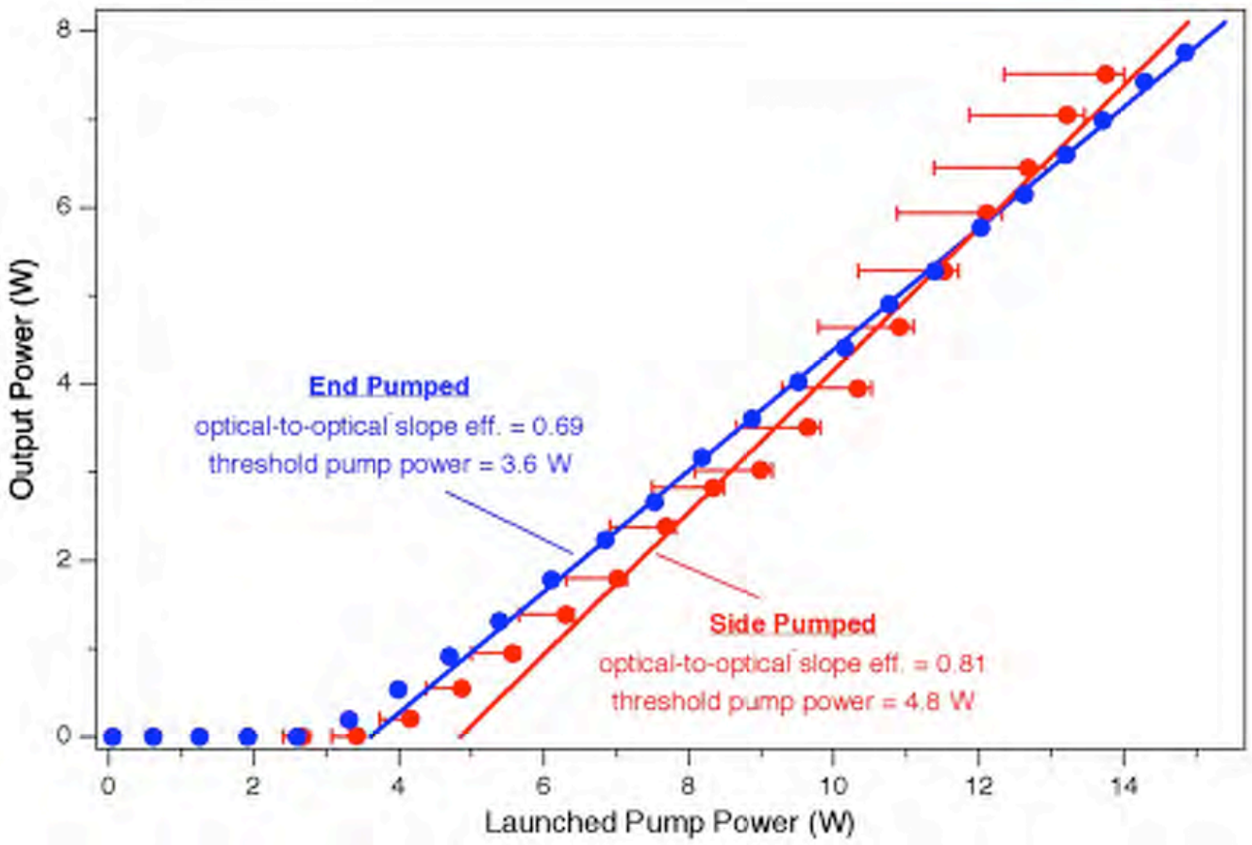
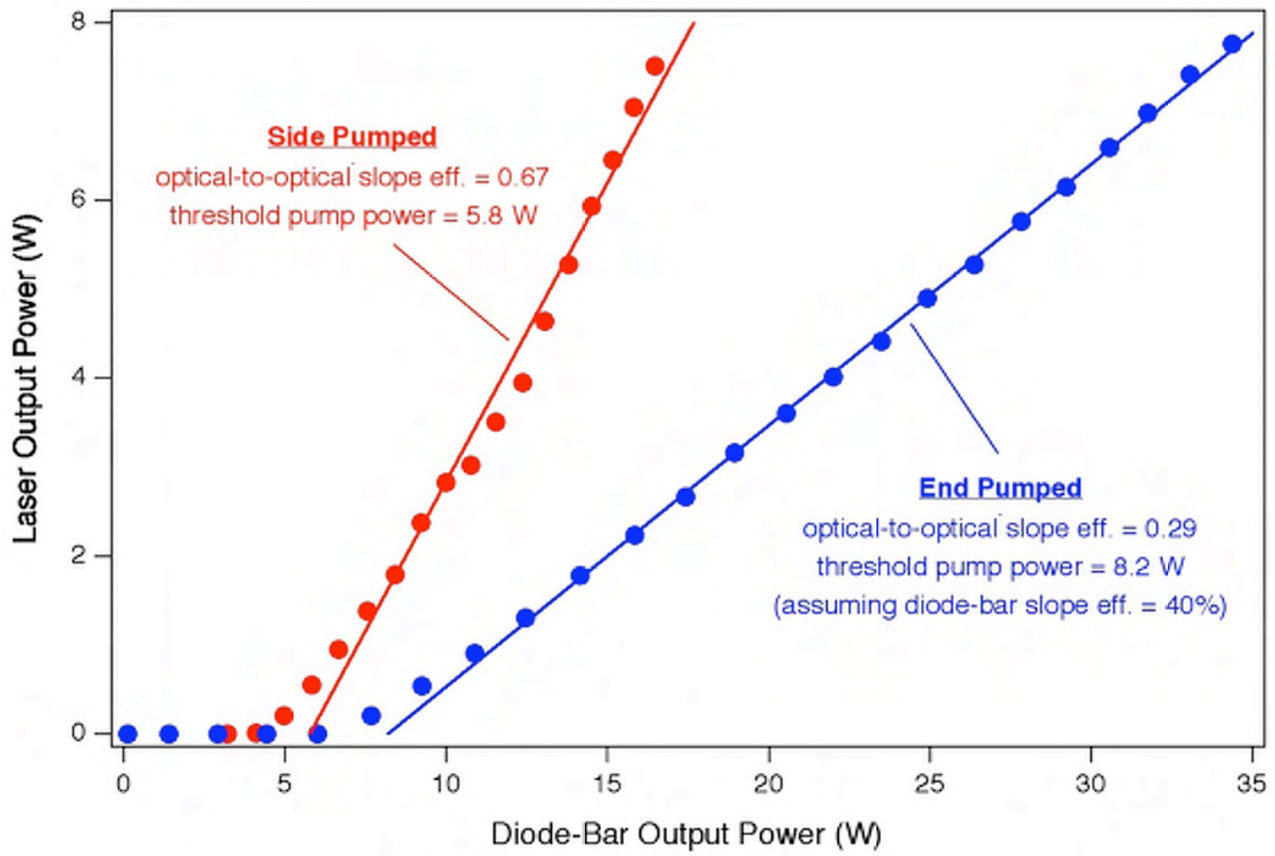
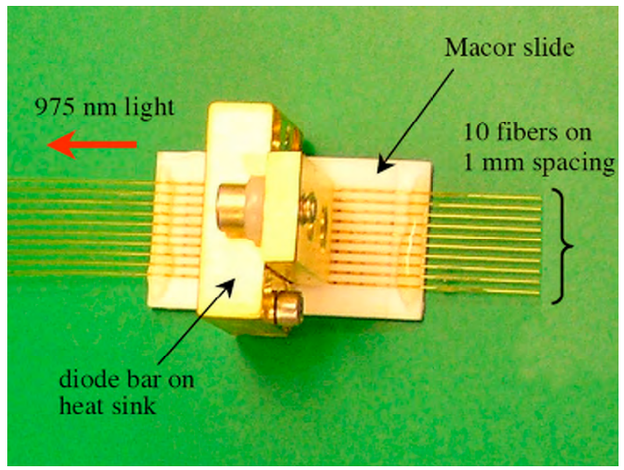
Diode-Bar-Pumped Fiber Laser





- EMSP efficiency higher by factor of 2.0
  - 44% (17 W) vs. 22% (35W) at 7.5 W output power



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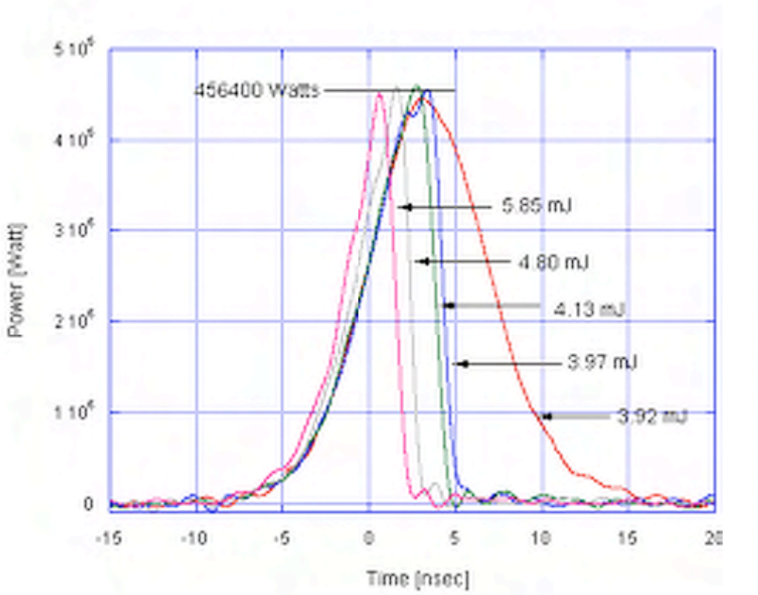
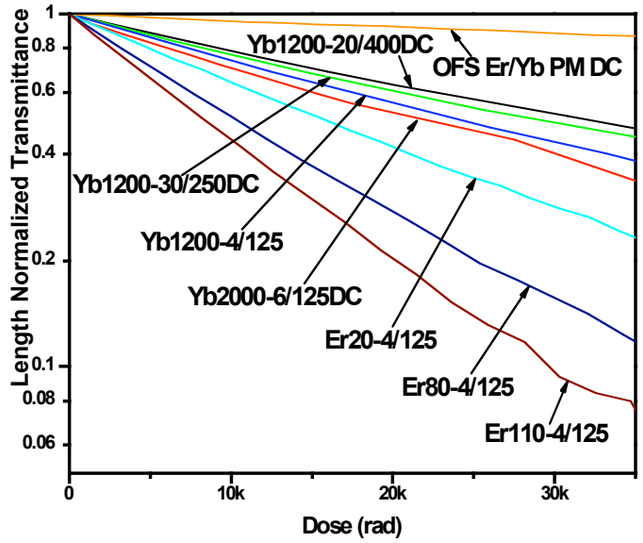
Other Activities

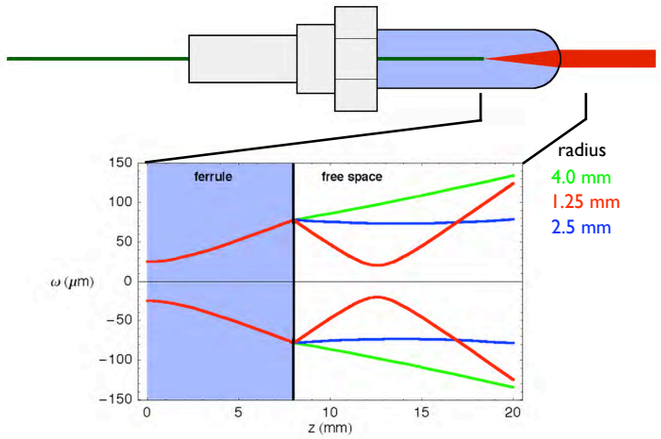
- Measurements of fundamental materials properties



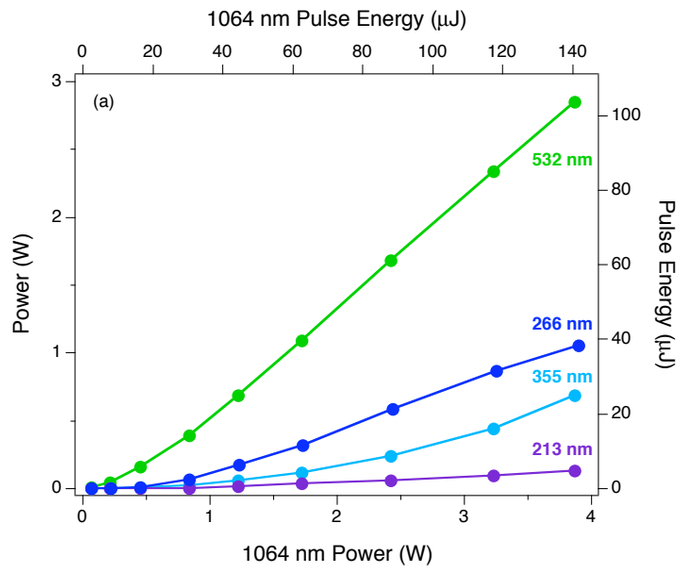
- Radiation testing of optical fibers



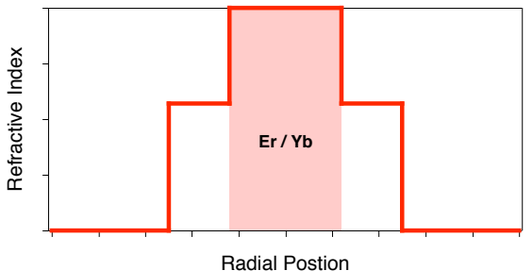
- Fiber end preparation

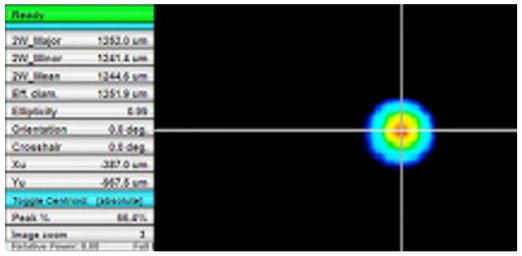


- Nonlinear frequency conversion

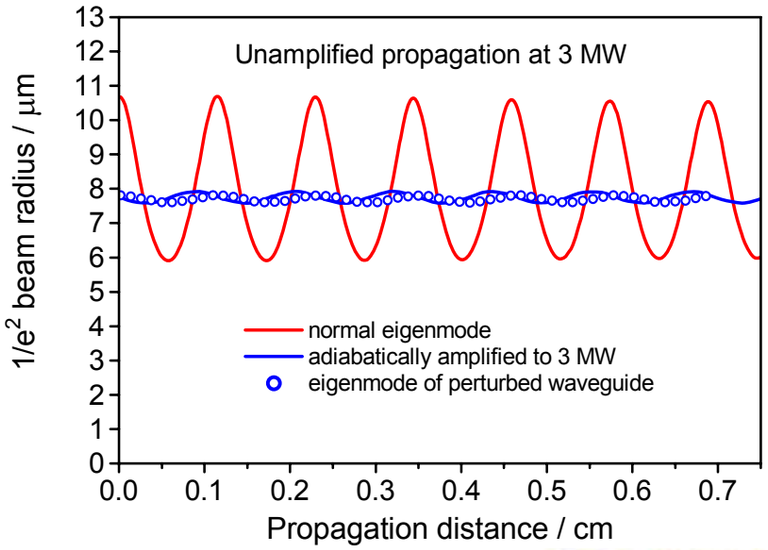


- Er/Yb-doped fiber





- Modeling of nonlinear processes in fiber



Personnel

Fiber-amplifier design, fabrication, and testing

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