Recent developments and potential challenges in high-power fiber lasers

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Outline:

- Background
- History
- Key components
- Applications
- Commercial success
- Challenges and solutions
- Conclusions
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Background

- **What is fiber laser?**
  - Core is made of rare earth doped silica
  - Optical power is confined in guided mode

- **Why are we interested?**
  - Diffraction-limited mode quality
  - Efficient heat removal
  - High efficiency (pump is confined)
  - Robust (potentially monolithic)
  - Low-loss silica, high damage threshold
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History

- **SM 10 kW (20kW)**
  - Rapid SM power growth before 2010
  - Mode quality limited by thermal effect

- **MM 120kW (500kW)**
History

- What makes the development take off at ~2000
  - Original fiber laser concept (Snitzer 1961/1964, Optical Optical Company)
  - Single-mode rare-earth doped fiber (Hegarty 1983, Bell; Poole 1985, Soton)
  - Double-clad fiber lasers (Snitzer 1988, Polaroid Corporation)
  - Fiber Bragg grating (Meltz and Morey, 1989, United Technology)
  - Pump combiners (early 1990s)
  - High-power diodes (late 1990s)
  - Telecom bubble burst (2001)

- Telecom bubble burst is the trigger
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Key components

- **Double-clad fibers**
  - High efficiency (O-O eff. 80-90%)
  - Efficient heat removal
  - High purity/damage threshold
Key components

- **Rare earth doping**
  - Notable dopants: Yb$^{3+}$, Er$^{3+}$, Tm$^{3+}$
  - No gas phase precursors
  - Solution doping is commonly used
Key components

- **High-power pump diode is a key enabling factor**
  - Fiber-coupled Single emitter diode (9xx E-O eff. ~50%)
    - ~10W in 105\(\mu\)m/0.15NA fiber
    - ~140W (200W) in ~106.5\(\mu\)m/0.22NA (135\(\mu\)m/0.15NA) fiber by combining diodes
    - Long lifetime (tested beyond 15,000hrs (3750 days), accumulated)
    - Used from low power to kW fiber lasers
    - Distributed architecture, ease of thermal management
  - **Fiber coupled diode bar (9xx)**
    - 1.5-3.5kW in 400\(\mu\)m/0.2NA
    - Single laser architecture (ease of switching pump)
    - Potentially lower lower cost
Key components

- **Pump combiners**
  - A variety of approaches explored initially
  - Standards have emerged based on standard fiber sizes

End pumping

Side pumping

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### Key Components

#### Pump Combiners

- A variety of approaches explored initially
- Standards have emerged based on standard fiber sizes

### Table

<table>
<thead>
<tr>
<th>Input fibers/Output fiber</th>
<th>125 μm DCF, NA = 0.46</th>
<th>250 μm DCF, NA = 0.46</th>
<th>400 μm DCF, NA = 0.46</th>
</tr>
</thead>
<tbody>
<tr>
<td>105 / 125 μm, NA = 0.15</td>
<td>7 x 1</td>
<td>19 x 1</td>
<td>61 x 1</td>
</tr>
<tr>
<td>105 / 125 μm, NA = 0.22</td>
<td>4 x 1</td>
<td>7 x 1</td>
<td>37 x 1</td>
</tr>
<tr>
<td>200 / 220 μm, NA = 0.22</td>
<td>1 x 1</td>
<td>4 x 1</td>
<td>7 x 1</td>
</tr>
<tr>
<td>400 / 440 μm, NA = 0.22</td>
<td>N/A</td>
<td>1 x 1</td>
<td>3 x 1</td>
</tr>
</tbody>
</table>

Assuming fully filled pump fibers

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### Diagrams

- End pumping configuration
- Side pumping configuration

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D. J. DiGiovanni US patent #5,864,644
Key components

- **Fiber Bragg gratings**
  - Integrated low-loss in-fiber reflector
  - Capable of multiple kW
Key components

- **Isolators**
  - Critical for isolation in MOPA
  - Fiber-to-fiber >20W is a challenge
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Applications

- Marking and printing
- Cutting and welding in manufacturing (automotive, smartphones, semiconductor, etc.)
- Micro-machining in precision machining, fuel injector, jet turbine, wafer dicing and repair
- Defense and security, sensing (LIDAR), Direct energy weapon
- Medical, Lasik, surgery, diagnosis
Applications

- **Yb ~1.05µm**
  - Highly efficient
  - Matured
  - Highest power

- **Er ~1.6µm (SM 200W)**
  - Eye safer
  - Lidar,
  - Laser ranging
  - Free-space communications

- **Tm ~2µm (SM 1kW)**
  - Lidar
  - High OH absorption
  - Surgery
  - Pumps for MWIR
Emerging Applications

- 3D printing
- Well drilling in oil industry
- Cutting/welding in hazardous environment (Reactor decommission)
- Particle accelerations
- Satellite launching
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Commercial success

- Near double-digit growth
- Revenue exceeded $1B in 2015
- Largest segments: Metal cutting (36%), marking (18%), semiconductor/PC/phone display (12%), micro-machining (11%),
Commercial success

- Metal cutting: few kW CW fiber lasers
- Marking, ns pulsed fiber lasers
- Glass/wafer cutting and micromicro-machining, ps/fs fiber lasers
Commercial success

- Low running cost is a major factor

### Cost Comparison: Fiber Laser vs. CO₂ Laser – High Power Cutting

<table>
<thead>
<tr>
<th></th>
<th>Fiber Laser (3kW)</th>
<th>CO₂ laser (4kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Overall System</strong></td>
<td>Full integration of laser and computerized motion system</td>
<td></td>
</tr>
<tr>
<td><strong>Wavelength dependence of material</strong></td>
<td>High material absorption, lower required power</td>
<td></td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td>50,000-100,000 hrs</td>
<td>20,000 hrs</td>
</tr>
<tr>
<td><strong>Power consumption</strong></td>
<td>$2,700/year (12hr shift)</td>
<td>$38,700/year (12hr shift)</td>
</tr>
<tr>
<td><strong>Consumables</strong></td>
<td></td>
<td>$35,000 (12hr shift)</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td></td>
<td>$45,000 (8hr shift)</td>
</tr>
<tr>
<td><strong>Power delivery</strong></td>
<td>Flexible cable</td>
<td>Mirrors and optical path</td>
</tr>
<tr>
<td><strong>Total cost of ownership</strong></td>
<td>$2,700/year (12hr shift)</td>
<td>$118,700/year (12hr shift)</td>
</tr>
</tbody>
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Further power scaling is critical

- Increased throughput in manufacturing
- Emerging applications:
  - Particle accelerations
  - Satellite launch
  - Space explorations
  - Laser-induced fusion
  - Direct energy weapons
  - ... 

Many of the emerging applications also need good mode quality
Challenges and solutions

- Nonlinear effects arise from high optical intensity is the major limit to power scaling:
  - Stimulated Brillouin scattering (SBS)
  - Stimulated Raman scattering (SRS)
  - Four-wave mixing (FWM)
  - Self-phase modulation (SPM)

- Need large mode area:
  - Most effective way to mitigate optical nonlinear effects
  - High energy storage leads to higher pulse energy

Nonlinearity limits peak power scaling!
Challenges and solutions

- **Mode area scaling**
  - Operating in the few-mode regime
  - Advanced designs to suppress high-order modes
    - Photonic crystal fiber
    - Leakage channel fibers
    - Chirally coupled core fibers
    - All-solid photonic bandgap fibers
Challenges and solutions

- Transverse mode instability (TMI) limits average power of single-mode fiber laser!

  - Interfering modes form traveling intensity waves

  ![Image](image1.png)

  - This intensity traveling wave generates a temperature wave in a fiber amplifier

  ![Image](image2.png)

  - The temperature wave leads to a traveling index grating, which couples more power to the higher-order mode

  ![Image](image3.png)

  - Positive feedback and self-enforcing like SBS

![Graph](graph.png)
Challenges and solutions

- Limited to ~3 kW in conventional LMA fibers
- Lower quantum defect by tandem pumping used in IPG 10kW fiber lasers can mitigate this at some level
- Thresholds in the order of 100-800W observed in large-mode-area PCFs
Challenges and solutions

- TMI is in fact Stimulated Thermal Rayleigh Scattering (STRS) discovered in the seventies.
- No new physics here!
- Recently we have experimentally confirmed the predicted gain STRS spectrum.

Challenges and solutions

- Record peak power of 4.5MW
- Rod-like 100µm-core PCF
- 1ns pulse, 4.3mJ, 42W average power, 9.6KHz, $M^2=1.3$

Challenges and solutions

- Record pulse energy of 26mJ
- Rod-like $135\mu$m-core PCF
- 55ns, 130W average power, 5KHz
- $M^2=1.3$)

Challenges and solutions

- Record directly diode-pumped CW power 4.3kW
- Ultra low-NA fibers, closer to SM regime
  - 0.42NA, 23µm core, $V \approx 2.8$, $M^2 = 1.27/1.21$

Challenges and solutions

- **All-solid photonic bandgap fibers**
- **Significant opportunity for high HOM loss**
  - Open cladding
  - Mode-dependent loss due to dispersive cladding
  - Robust single-mode regime due to strong dispersive cladding
Challenges and solutions

- **Multiple-cladding-resonance (MCR) fiber:**
  - Introduce strongly-coupled small cladding cores in resonance with HOM in the main core:
    - Strong coupled cladding cores enable broad resonance
    - Ease of implementation
    - Open cladding enables strong coupling

Ytterbium-doped 50/400 MCR all-solid PBF

- Pump Light @980nm
- Emission @1030nm
- 5.3m fiber @ 70cm coil
- 50µm/400µm
- pump NA=0.46
- 2.3dB/m at 976nm

- ~950W @1025nm
- $M^2_x=1.39$, $M^2_y=1.3$

Graphs:

- Laser output vs launched pump (W)
- Laser output vs absorbed pump (W)

Equation:

$y = 0.8389x - 25.154$
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Conclusions:

- Unique convergence of technologies and events kicked off the rapid development of fiber lasers at the dawn of the 21st century
- Fiber lasers are reshaping our manufacturing in 21st century
- Revenue exceeded $1b in 2015
- A range of very exciting emerging applications demand further power scaling
- Challenges and opportunities abound
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