New Technologies of Solid State Lasers for Materials Processing

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Outline

• Quick review of fiber-laser designs
• Diode pump lasers for bulk and fiber lasers
• The battle for cw power
• The changing boundaries of short-pulse lasers
• Future directions - photonic fibers
• Summary

Will be available at www.qpeak.com/Research/recent_technical_papers.htm
Quick review of fiber-laser designs
Cladding-pumped fiber laser allows multimode pumping of single-mode cores

Elias Snitzer first described cladding pumped lasers in 1988

Maurer, U.S Patent 3,808,549 (April 30, 1974)

J. Kafka, U.S. Patent 4,829,529 (May 9, 1989)
Non-circularly symmetric cladding geometries permit effective overlap with laser core.

Absorption length is increased by the ratio of cladding to core areas

http://www.iap.uni-jena.de/fawl/rdtfawl.html
End-pumped double-clad requires dichroic mirrors and “bright” pump source.

Ytterbium-doped large-core fiber laser with 1 kW continuous-wave output power

Lucent design allowed access to end of fiber and multiple pump ports

D. J. DiGiovanni US patent #5,864,644
Multi-Mode Coupler Region

- Multi-Mode coupler is created by fusing under high temperature conditions double-clad doped fiber with multi-mode fiber from pump source
SPI has GTWave Technology

> 70 W per module
Beyond double-clad designs, further strategies are needed for fiber-laser power scaling

- Eventually, the small area of the mode in the core creates limits:
  - Optical damage to the fiber faces (more later)
  - Bulk damage at flaws or defects
  - Nonlinear optical effects in the bulk of the fiber

- Nonlinear effects include:
  - Stimulated Brillouin scattering for single-frequency sources, cw or pulsed > 10 ns
    - Adds frequency components and can lead to backward wave generation and catastrophic pulse shortening
    - Threshold follows (Core area)/(Fiber length)
  - Stimulated Raman scattering
    - Adds frequency components, may limit NL conversion
    - Threshold follows (Core area)/(Fiber length)
  - Self phase modulation

- Larger core/mode size is desirable – lower intensity and shorter fiber length for double-clad designs
Step index fiber - limits for single mode

\[ NA = \sin(\theta_{\text{max}}) \]

\[ NA_{\text{step}} = \sqrt{n_f^2 - n_c^2} \]

\[ V = 2\pi \frac{a}{\lambda_o} NA \]

\[ a \text{ is core radius, } \lambda \text{ is wavelength} \]

\[ V < 2.405 \text{ for single-mode fiber} \]
Relation of core diameter to NA for step-index fiber

Below a NA of 0.06 or so, bend losses are problematic.
Coiling fiber allows single-mode with $V > 2.4$

25 um core diameter, NA 0.1 ($V=7.4$ at 1064 nm)

Other tricks around the core size limits

Complex index profiles
(also good for wavelength discrimination)

J.A. Alvarez-Chavez et al.,

Tapered sections

http://www.orc.soton.ac.uk/hpfl/tapers.php

Careful launching of low-temporal coherence,
single-mode beam into high-quality, thick cladding, multimode fiber

Or, Photonic Crystal Fibers (PCF) - more later
Diode pump lasers for bulk and fiber lasers
JDSU 5-W 915-nm diode laser
Telcordia-qualified, long-lifetime pump

JDS Uniphase's ultra-reliable 6390 series laser diodes offer 5 W of laser power from a 100 µm fiber into 0.2 NA. The L3 package is a redesign of the existing fiber-coupled L2 package, incorporating telecom design approaches into a commercial product and resulting in a reliability of >200,000 hours MTBF.
Coherent 808nm 30W FAP-B
MTTF: 47000hrs (90% CL)

Normalized Power vs. Time (hrs)
### DARPA (Martin Stickley) SHEDS Program (PhAST PTuD2)

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Current</th>
<th>18 Mo.</th>
<th>36 Mo.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar power conversion eff.</td>
<td>50%</td>
<td>65%</td>
<td>--</td>
</tr>
<tr>
<td>Bar power output</td>
<td>80W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stack PCE</td>
<td>50%</td>
<td>--</td>
<td>80%</td>
</tr>
<tr>
<td>Stack Power</td>
<td></td>
<td>480W</td>
<td></td>
</tr>
<tr>
<td>Spectral Width</td>
<td>10-15nm</td>
<td>2nm</td>
<td>2nm</td>
</tr>
<tr>
<td>Uniformity of wavelength across the emitting area</td>
<td>±10nm</td>
<td>±0.5nm</td>
<td>±0.5nm</td>
</tr>
</tbody>
</table>

**NLight data**

![NLight data graph](image)
High-brightness pump sources

- Apollo Instruments fiber-coupled diode lasers (0.22 NA):
  - 35 W from 100 um
  - 150 W from 200 um
  - 400 W from 400 um
  - 500 W from 600 um, 0.22 NA fiber
- Laserlines stacked, beam-shaped bars
  - 500 W, 40x50 mrad
  - 1000 W, 60x80 mrad
  - 6000 W, 85x400 mrad
- Nuvonyx stacked, beam-shaped bars
  - 4000W, focusable to 12.5 x 0.5 mm spot
The battle for cw power
Toshiba and Shibaura diode-pumped Nd:YAG rod lasers

Shibaura LAL-210/220/230/240/260 SERIES 4.5 kW with 600 um fiber

“Toshiba succeeded in obtaining an output power of 12 kW with an efficiency of 23 %, which are, to our knowledge, the highest values for a Nd:YAG laser.”
“Mitsubishi Electric recently announced an all-solid-state laser that is the world's most efficient laser of its kind. The new laser converts 23% of the electrical power it receives into light energy. That is more efficient than any other solid-state laser.”

$P_{cw} = 1\ kW$, $P_{pulse} = 10\ kW$, focusable to 50 um
<table>
<thead>
<tr>
<th>Laser device</th>
<th>Max. output power (Watts)</th>
<th>Laser power at the workpiece (Watts)*</th>
<th>Beam quality (mm * mrad)</th>
<th>Laser light cable (microns)</th>
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</thead>
<tbody>
<tr>
<td>HLD 1003</td>
<td>1300</td>
<td>1000</td>
<td>12</td>
<td>300</td>
</tr>
<tr>
<td>HLD 3504</td>
<td>4500</td>
<td>3500</td>
<td>16</td>
<td>400</td>
</tr>
<tr>
<td>HLD 4506</td>
<td>6000</td>
<td>4500</td>
<td>25</td>
<td>600</td>
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<tr>
<td>ROFIN DY 022</td>
<td>ROFIN DY 027</td>
<td>ROFIN DY 033</td>
<td>ROFIN DY 044</td>
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<td>-------------</td>
<td>-------------</td>
<td>-------------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td><strong>Excitation</strong></td>
<td>Laser diodes</td>
<td>Laser diodes</td>
<td>Laser diodes</td>
<td>Laser diodes</td>
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<tr>
<td><strong>Output power</strong></td>
<td>2200 W</td>
<td>2700 W</td>
<td>3300 W</td>
<td>4400 W</td>
</tr>
<tr>
<td><strong>Beam parameter product</strong></td>
<td>12 mm*mrad</td>
<td>12 mm*mrad</td>
<td>12 mm*mrad</td>
<td>12 mm*mrad</td>
</tr>
<tr>
<td><strong>Fiber diameter</strong></td>
<td>400 µm</td>
<td>400 µm</td>
<td>400 µm</td>
<td>400 µm</td>
</tr>
</tbody>
</table>
Average power thermal limits for fibers

Evaluated by Brown and Hoffman, IEEE JQE 37, 207 (2001)

For 9.2-um core, 600 um fiber diameter

34 kW/m of heat generation leads to fracture

48 W/m of heating leads to silica melting in center for static air cooling

but 100 W/m of heating demonstrated in practice without problems (Y. Jeong, Southampton, LEOS 2003 Annual)

Heat generation in YDFLs ~15% of output power: 150 W/kW

→ ~1 kW/m optical power generation in efficient YDFLs

Limit to power is not fracture or index gradient but “core meltdown”

Future systems may use water cooling to increase power/length
# High-power cw fiber laser results

<table>
<thead>
<tr>
<th>Group</th>
<th>Power (W)</th>
<th>Lambda (nm)</th>
<th>$M^2$</th>
<th>Core (um)</th>
<th>NA</th>
<th>L (m)</th>
<th>Pump (W)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SORC</td>
<td>610</td>
<td>1098</td>
<td>1.3</td>
<td>43</td>
<td>0.09</td>
<td>9</td>
<td>1000</td>
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<tr>
<td>/SPI</td>
<td>1010</td>
<td>1096</td>
<td>3.4</td>
<td>43</td>
<td>0.09</td>
<td>8</td>
<td>1500</td>
<td></td>
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<tr>
<td></td>
<td>264</td>
<td>1060</td>
<td>&lt;1.1</td>
<td>25</td>
<td>0.06</td>
<td>7</td>
<td>500</td>
<td>SF, pol.</td>
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<tr>
<td></td>
<td>120</td>
<td>1565</td>
<td>1.9</td>
<td>30</td>
<td>0.06</td>
<td>4</td>
<td>325</td>
<td></td>
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<tr>
<td>U. Mich.</td>
<td>155</td>
<td>Yb</td>
<td>1.32</td>
<td>30</td>
<td>0.06</td>
<td>25</td>
<td>475</td>
<td>Pol,coil</td>
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<tr>
<td>/Fraun.</td>
<td>700</td>
<td>1092</td>
<td>1.42</td>
<td>20</td>
<td>0.06</td>
<td></td>
<td>970</td>
<td>coil</td>
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<tr>
<td>NGST</td>
<td>155</td>
<td>1083</td>
<td>1.17</td>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>SF, pol.</td>
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<tr>
<td>IPG</td>
<td>300</td>
<td>Yb</td>
<td>&lt;2</td>
<td></td>
<td></td>
<td></td>
<td>YLR-300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>Yb</td>
<td>&lt;4</td>
<td></td>
<td></td>
<td></td>
<td>YLR-700</td>
<td></td>
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<tr>
<td></td>
<td>250</td>
<td>1076</td>
<td>1.04</td>
<td>14</td>
<td></td>
<td></td>
<td>450</td>
<td>Pol.</td>
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<tr>
<td>Jena</td>
<td>310</td>
<td>Yb</td>
<td>1.1</td>
<td>20</td>
<td>0.07</td>
<td>45</td>
<td>400</td>
<td>Pol.</td>
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<tr>
<td></td>
<td>1300</td>
<td>1090</td>
<td>&lt;3</td>
<td>38</td>
<td>0.06</td>
<td>50</td>
<td>2200</td>
<td>launched</td>
</tr>
</tbody>
</table>

**CLEO 2004 Session CMS**

**CLEO 2004 Postdeadline**
SORC/SPI results for first >1 kW single-fiber laser

- Measured
- Linear fit
- Slope efficiency: 80%

Signal power [W]

Launched pump power [W]
IPG Photonics YLR-HP Series:
1-10kWatt Ytterbium Fiber Lasers

- Up to 10 kW Output Optical Power
- Over 20% Wall-Plug Efficiency
- Excellent Beam Parameter Product
- >50,000 Hours Pump Diode Lifetime
- Air or Water Cooled Versions
- Maintenance Free Operation
- Up to 200 m Fiber Delivery
- 2 Year Warranty

*Latest performance, May 2004
5.5 kW, 4.3 mm-mrad, 100-um fiber delivery*
New “bulk” laser technology: thin-disk lasers
Single thin disk generates 500 W, 50% efficiency

A. Giesen “Thin disk lasers: recent results and future prospects”
SPRC Annual Meeting, September, 2003
Summary of thin disk results, late 2003

- Trumpf-Laser: 4 kW thin disk laser, $M^2 < 20$, $\eta > 25\%$
- Jenoptik L.O.S.: Thin disk laser up to 8 W green (532 nm), 0.8 W blue (457 nm), 2 W red (660 nm). Q-switch thin disk laser
- ELS: Fundamental mode thin disk laser up to $P > 100$ W c.w., $> 15$ W green
- Rofin-Sinar 750 W, 1.5 kW, 3 kW thin disk laser

Data achieved in laboratory:
- Rofin-Sinar $P > 1.5$ kW out of one disk
- Trumpf-Laser $P > 2$ kW out of one disk

A. Giesen “Thin disk lasers: recent results and future prospects”
SPRC Annual Meeting, September, 2003
Laser parameters for materials processing

\[ Q = \theta_f \cdot \sqrt{\frac{P}{I \cdot \pi}} \]

Beam parameter product \( Q \) vs. laser power \( P \)

- **Printing, therm. marking**
- **Plastics welding**
- **Soldering**
- **Selective laser powder remelting**
- **Metal sheet cutting**
- **Deep penetration welding metals**
- **Transformation hardening**
- **Melting, cleaning**
- **Lamp pumped Nd:YAG-laser**
- **CO₂-laser**

Laser types:
- F#4 focusing optics (NA 0.12)
- Diodelasers (2003)

**Courtesy Peter Loosen, ILT**
Advanced diode-pumped solid state lasers applied to materials processing

Laserpower $P$ [W]

Beam parameter product $Q$ [mm mrad]

- Printing therm. marking
- F#4 focusing optics (NA 0.12)
- soldering
- plastics welding
- selective laser powder remelting
- transformation hardening
- deep penetration welding metals
- metal sheet cutting
- brazing
- cleaning, melting
- selective laser powder remelting
- F#4 focusing optics (NA 0.12)
- F fiber
- D disk
- R rod

Focusing optics (NA 0.12)
- F#4 focusing optics (NA 0.12)
- F fiber
- D disk
- R rod

Printing therm. marking
- Printing therm. marking
- F#4 focusing optics (NA 0.12)
- F fiber
- D disk
- R rod

Laserpower $P$ [W]

Beamparameterproduct$Q$[mmmrad]
• Single-mode fibers to the 3 kW level?
• Fiber laser bundling can provide > 10 kW
• Phased arrays of fiber lasers
• The Empire Strikes Back:
  – US High-Energy Laser Program (HEL JTO) funding two 25 kW bulk solid state laser demonstrations at Raytheon and TRW
The changing boundaries of short-pulse lasers
Yb pulsed fiber lasers not ready for NIF

Glass Slab LRUs being prepared for transport from the Optics Assembly Building (OAB) into Laser Bay 2. The drawing on the right shows a cut-away view of a NIF amplifier with glass slabs and flashlamps.
Extractable energy from Yb-doped fibers limited by ASE at low pulse rates

Renaud et al. JQE 37, 199 (2001)
LLNL surface damage data for fused silica

![Graph showing pulsewidth dependence of threshold damage fluence for fused silica at 1053 nm (•) and 825 nm (♦).](image)

Fig. 5. Pulsewidth dependence of threshold damage fluence for fused silica at 1053 nm (•) and 825 nm (♦).

B. C. Stuart, M. D. Feit, S. Herman, A. M. Rubenchik, B. W. Shore, and M. D. Perry
End-face damage limits (calculated) for different pulsewidths

![Graph showing end-face damage limits for different pulsewidths. The x-axis represents mode diameter (um), the y-axis represents damage pulse energy (mJ), and the graph includes curves for pulsewidths of 0.001, 0.01, 0.1, 1, and 10 ns.]
Comparison of end-face damage calculations and (limited) data

![Graph showing comparison between Fibertek and Southampton data](image-url)

- Fibertek data
- Southampton data

- Damage intensity (GW/cm²)
- Damage fluence (J/cm²)
- Pulsewidth (ns)
Latest pulsed fiber-laser results

- CLEO 2004 Paper CTuS4 M-Y Chen et al. (U. Mich, OADS)
- With Yb-doped, 200 um NA 0.062, core, 600 um clad, coiled fiber
  - 82 mJ in 500 ns
  - 27 mJ in 50 ns
  - 9.6 mJ in 4 ns (2.4 MW)
- $M^2 = 6.5$, 25 Hz, pump energy 560-800 mJ in 4 ms
- Used end-caps, but now close to bulk-damage, self-focusing limits in silica
100-W average power, Yb pulsed fiber laser

25 m 30 um core NA 0.06 V=5
500 ppm Yb$_2$O$_3$
Coiled < 10 cm radius
End cap, exit beam 150 um radius
200 W pump laser
100 GHz linewidth Nd:YAG seed

50 ns pw at 3 kHz (80 kW)
300 ns pw at 50 kHz (6.7 kW)
100 W average at 50 kHz
$M^2 = 1.1$, unpolarized

J. Limpert et al.
MPS design for high-efficiency, TEMoo-mode systems

I/O performance with Nd:YLF at 1047 nm cw oscillator

Multi-Pass Slab (MPS)

Nd:YLF is “athermal” material
0.5 diopter lens at 80 W pump

Birefringence eliminates depolarization

\[ M^2 = 1.05 \]
MPS Nd:YLF amplifier chain extracts 20-25 W per stage with minimal beam degradation.

Short-pulse, AO Q-switched Nd:YLF laser

30-100 kHz, 6.5-20 nsec
1.5 W average

85 W average power at 1047 nm for 250 W of diode power
At 30 kHz:
2.8 mJ/pulse
6.5 ns
435 kW
polarized
M^2 < 1.3
Bulk lasers provide the peak and average powers needed for high-power UV generation.
Future directions - photonic fibers
PCF fundamentals

- Photonic crystal (or holey) fibers are fabricated with structured “holes” in fiber cross section.
- The region with holes has a lower and adjustable refractive index, with tunable dispersive properties.
- For fiber lasers, applications include:
  - Replacing polymer cladding with low-index holey section, eliminating chance of polymer “burn” and increasing NA of cladding.
  - Allowing very low refractive change, for larger core mode sizes (reduced bending losses observed).
ORC 366 W Yb fiber laser with “air jecket”

Y. Jeong, Southampton, LEOS 2003 Annual

Also: J. Limpert et al. Thermo-optical properties of air-clad photonic crystal fiber lasers in high power operation, Opt. Ex. 11, 2982 (2003)
Conclusions

- Fiber lasers have reached cw power levels formerly only possible with bulk-crystal designs, and have somewhat better beam quality.
- The simplifications in cooling the active medium compared to bulk lasers are countered by the need for higher-brightness pump sources.
  - “Side-pumped” schemes (IPG, SPI) are advantageous.
- Acceptance of competing technologies (rod, thin disk and fiber) for materials processing will depend on factors other than beam quality, total cost of ownership being the most significant.
- For short-pulsed systems, bulk lasers will “always” be capable of higher energies and peak powers, but fiber lasers can provide a new operation space (e.g. MHz pulse rates) that would be difficult with bulk systems.