High-Power, Tm-Fiber-Laser-Pumped, Ho:YLF Laser

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Solid State Lasers
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I just talk, Alex does the work
Motivation

- Development of a 2050-nm laser source:
  - High-energy (> 200 mJ)
  - High repetition rate (200-1000 Hz)
  - High beam quality (TEM$_{00}$)

- Immediate applications:
  - Industrial (laser materials processing)
  - Military (eye-safe, long-range 2D and 3D imaging, coherent systems for Doppler and vibrometry sensing)
  - Pump source for OPOs (laser acoustics, IRCM, chem-bio standoff detection)
Why a laser pumping a laser pumping a laser?

- **Semiconductor diode laser**
  - high electrical-optical efficiency *but*
  - only cw-like output, poor beam quality at high powers

- **Fiber solid state laser**
  - good (in theory) conversion of poor quality beam from diode lasers into diffraction-limited beam *but*
  - limitations in stored energy and nonlinear/damage issues prevent generation of high pulse energies

- **Bulk solid state laser**
  - good conversion of pump power to output power
  - high energy storage and extraction capability allows generation of high-peak-power pulses
Ho:YLF vs. Ho:YAG

- **Why Ho:YLF (Q-Peak, NASA)?**
  - Long upper laser level lifetime ~ 15 ms (in theory)
  - Highest emission cross-section known for Ho-doped crystals
    \[ \sigma = 1.84 \times 10^{-20} \text{ cm}^2 \]
  - \( E_{\text{sat}} = 5.3 \text{ J/cm}^2 \)
  - Naturally birefringent material
  - Low \( \frac{dn}{dT} \rightarrow \) weak thermal lensing
  - ~5% quantum defect

- **Compared to Ho:YAG (BAE, SORC)**
  - Upper state lifetime 7 ms
  - Emission cross section \( 0.98 \times 10^{-20} \text{ cm}^2 \)
  - \( E_{\text{sat}} = 9.6 \text{ J/cm}^2 \)
  - 10% quantum defect
  - Isotropic, higher thermal lensing, stress birefringence
  - Superior thermo-mechanical properties
Ho:YLF absorption data yields prediction of emission cross section.
Ho:YLF gain is predicted to be high for a 59% inversion fraction
2001
- Tunable Tm:YLF laser (>15 W )

2003
- Single Ho:YLF-crystal oscillator pumped with two Tm:YLF lasers (~50 W total power)

2005
- Double Ho:YLF-crystal oscillator pumped with one 100-W Tm:fiber laser

2006
- Single Ho:YLF-crystal oscillator followed by three amplifiers pumped with two Tm:fiber lasers ( ~230 W total power)
Prior Ho:YLF laser operation demonstrated high pulse energies with excellent mode quality.

**CW output:** 21 W (max)

**Pulse energy (max):**
- 100 Hz: 35 mJ
- 400 Hz: 27 mJ

**Pulsewidth:**
- 100 Hz: 12 ns
- 400 Hz: 15 ns
Ho-laser power scaling is possible with Tm:fiber-laser pumps

- CW Tm:fiber commercial lasers with output >100 W have emerged as alternative to bulk Tm-laser:
  - Turn key operation based on industrial designs developed for Yb:fiber lasers
  - Cost-effective in terms of $/W
  - Maintenance-free (we hope)
  - Fiber delivery (no surprise!)
Tm-pump laser requirements are satisfied (mostly) by commercial IPG laser

Specific requirements for Tm-laser as a pump source for Ho:YLF:

- Linear polarization (preferably)
- Lasing wavelength at ~ 1940 nm
- Linewidth < 6 nm

Tm-fiber laser TLR-100-1940
(IPG Photonics, www.ipg photonics.com)

<table>
<thead>
<tr>
<th>Operation regime</th>
<th>CW</th>
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<tbody>
<tr>
<td>Operational temperature</td>
<td>RT</td>
</tr>
<tr>
<td>Output power</td>
<td>≥ 100 W</td>
</tr>
<tr>
<td>Lasing wavelength range:</td>
<td>1750-2200 nm</td>
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<tr>
<td>Polarization:</td>
<td>Random</td>
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<tr>
<td>Linewidth</td>
<td>≤ 2 nm</td>
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Tm:fiber laser pumped single-crystal Ho:YLF oscillator

DM – Dichroic Mirror,
AOM – Acousto-Optic Modulator,
OC – Output Coupler,
HR – High Reflector
**Ho:YLF MOPA chain**

- **Tm-fiber laser 120 W**
  - Ho-osc
  - Ho-Amp #1

- **Tm-fiber laser 110 W**
  - Ho-Amp #2
  - Ho-Amp #3

- **Tm-fiber laser 100 W**
  - Ho-Amp #4
  - Ho-Amp #5

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<tr>
<th></th>
<th>CW</th>
<th>500 Hz</th>
<th>1000 Hz</th>
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<tr>
<td><strong>Master osc</strong></td>
<td>19 W</td>
<td>25 mJ</td>
<td>17 mJ</td>
</tr>
<tr>
<td><strong>Amp 1</strong></td>
<td>42 W</td>
<td>55 mJ</td>
<td>38 mJ</td>
</tr>
<tr>
<td><strong>Amp 2</strong></td>
<td>60 W</td>
<td>90 mJ</td>
<td>58 mJ</td>
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<tr>
<td><strong>Amp 3</strong></td>
<td>78 W</td>
<td>115 mJ</td>
<td>73 mJ</td>
</tr>
<tr>
<td><strong>Amp 4</strong></td>
<td>97 W</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td><strong>Amp 5</strong></td>
<td>113 W</td>
<td>***</td>
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*** work in progress
Tuning curve for Ho:YLF-pumped ZGP OPO shows broad mid-IR coverage.
ZGP OPO data on pulse energy at 3200 nm shows no significant average-power limitations.

Slope efficiency:
- 50 Hz: 60%
- 200 Hz: 56%
- 400 Hz: 63%
Highly doped Tm fiber lasers demonstrate high efficiency

Conclusions

• Fiber-laser pumped Ho:YLF crystals (and similar materials) combines best features of fiber and bulk solid state lasers
  – High beam quality and powers of fiber lasers
  – Energy storage capability of bulk lasers
• Recent advances in commercial (IPG) Tm:fiber lasers have made 100-W devices available.
• Ho:YLF laser has a favorable combination of energy storage and high gain cross section, suitable for high-energy, short-pulse Q-switched oscillators and amplifiers at 2050 nm
• 2050-nm wavelength is eyesafe, transmits well through the atmosphere and is a good pump wavelength for ZGP OPOs providing coverage of entire mid-IR wavelength region
• The results reported are, to the best of our knowledge the highest powers and energies yet achieved with Ho:YLF lasers
• High-efficiency Tm:fiber pump lasers are on the horizon
Backup
DM – Dichroic Mirror,
AOM – Acousto-Optic Modulator,
OC – Output Coupler,
HR – High Reflector
Double oscillator: 40 W of cw power
40 mJ of Q-switched energy in 17-ns pulse
Ho-laser efficiency

- In order to achieve efficient Ho-operation
  - High optical density
  - Tight focusing to deplete (bleach) the ground state
- This works well in CW regime
- However, in Q-switched regime it is necessary to avoid the damage of all optical components
- A few examples:
  - We assumed generation of 10 mJ pulses with 15 ns pulsewidth
  - We took the values for the mode size and OC reflectivity from different Ho-papers and calculated intracavity energy/power density

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<tr>
<th></th>
<th>Roc</th>
<th>Beam Radius, um</th>
<th>Av. energy density, J/cm²</th>
<th>Av. power density, MW/cm²</th>
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<tbody>
<tr>
<td>Q-Peak</td>
<td>0.3</td>
<td>0.45</td>
<td>2.9</td>
<td>195</td>
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<tr>
<td>ORC</td>
<td>0.8</td>
<td>0.23</td>
<td>54</td>
<td>3600</td>
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<tr>
<td>BAE</td>
<td>0.85</td>
<td>0.28</td>
<td>50</td>
<td>3340</td>
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CW laser operation provides 40-W of output power.

Output transmission

- Slope Efficiency 42%
- Quantum efficiency 74% (absorbed)

Graph showing the relationship between Total Tm-pump power, W and Ho:YLF output, W for 40% and 70% transmission.
Ho:YLF Q-switched laser operation observed at pulse rates from 200-1000 Hz

We chicken out

"Moderate" focusing

"Loose" focusing

Total Tm-pump power, W

Ho:YLF pulse energy, mJ
Ho:YLF effective storage time is around 2 msec based on energy vs. pulse rate data.

Reasons: Bleaching, upconversion?
Absorption saturation in 2% Ho-doped YLF at 1940 nm shows reduced lifetime.

![Graph showing transmission vs. power density]