Progress in Hybrid Fiber/Bulk Solid State Lasers

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Outline

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  - Pump sources for GSD lasers
- Ho-properties – brief overview
- Tm:fiber Laser – Details
- Previous Results
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- Ho:YLF Laser – Details
- Conclusions
Motivation

- Development of an IR laser source:
  - High-energy (> 200 mJ)
  - High repetition rate (200-1000 Hz)
  - High beam quality (TEM\textsubscript{00})

- Immediate applications:
  - Pump source for OPOs
  - Lidar
  - Medical, industrial, military
Ground state depleted lasers

- Yb, Er, Ho, Tm lasers are examples of ground state depleted (GSD) lasers.

- GSD laser operates as a quasi-4-level system:
  - Pumping is accomplished into the 1st excited manifold.
  - Lower laser level belongs to the ground manifold and is partially populated at room temperature.
  - GSD laser can not be [1-quantum-defect]-efficient at RT !!!

- Fundamental spectroscopic and laser properties pertinent to GSD lasers are systematically and quantitatively analyzed in prior work at LLNL:

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Why Ho-lasers?

- Most of the laser transitions in 2-um region have such a low gain cross-section that efficient, high-energy laser oscillation or amplification is impossible:
  - The energy fluence required for efficient extraction of stored energy in the laser material is so high that they will lead to optical damage of the laser crystal or associated optics.

- Only Ho-doped crystals, including Ho:YAG and Ho:YLF, have a large enough gain cross-section for effective high-energy operation.
  - Ho:YAG $\sigma_{em} \sim 1 \times 10^{-20}$ cm$^2$
  - Ho:YLF $\sigma_{em} \sim 2 \times 10^{-20}$ cm$^2$
Approaches to diode-pumping of Ho-doped lasers

- 780-790-nm diode lasers → Tm, Ho-laser
- 780-790-nm diode lasers → Tm-laser → Ho-laser
- 940-980-nm diode lasers → Er-laser → Tm-laser → Ho-laser
- ~1900-nm diode lasers → Ho-laser
Advantages of Tm-pumped Ho-laser

- Compared to diode-pumped Tm, Ho-co-doped laser:
  - Eliminates upconversion from Tm-Ho interaction that reduces efficiency and creates additional heating in crystal
  - Eliminates energy sharing between Tm and Ho that limits energy extraction in Q-switched mode

- Compared to direct-diode-pumped Ho-laser
  - Can operate at much higher power due to availability of high-power Tm-lasers

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Pump sources for Ho-laser

- Relatively high-brightness sources are required (preferably $M^2<10$)
  - GSD laser pumping requires high optical density $\alpha L >> 1$
- 1850-1950 nm wavelength range
- High power to achieve Ho-output $>>10$ W
- Possible alternatives:
  - Diode-pumped Tm-bulk solid state lasers
  - Diode-pumped Tm:fiber lasers Er or Tm
Ho-laser power scaling

- Cw Tm:fiber lasers with output >100 W emerge as an alternative to bulk Tm-laser:
  - Turn key operation
  - Cost-effective
  - Maintenance-free
  - Fiber delivery (no surprise!)
  - Excellent beam quality
  - Scalable power
  - Wide tuning range
  - Commercially available
Previous results – Ho-lasers

- **Tm:YLF pumped Ho:YAG**
  - **Tm:YLF pump**
    - 36 W CW output at 1907 nm (σ-line)
    - Multimode, $M^2 \sim 2$
  - **Ho:YAG**
    - CW: 19 W
    - QS: 16 W at 15 kHz

- **Tm:YLF pumped Ho:YLF**
  - **Tm:YLF pump**
    - 2 x ~25 W CW output at 1940 nm (σ-line)
    - $M^2 \sim 1.05 \times 7$
  - **Ho:YLF**
    - CW: 21 W
    - QS: 16 W at 1 kHz

- **Ho-lasers pumped with Tm:fiber lasers:**
  - ORC, Univ. of Southampton, UK (Ho:YAG) ASSP’03 (A.Agdolvand et al., TOPS Vol.83, 7 (2003))
  - NASA (Ho:YLF)
  - FFI (Forsvarets forskningsinstitutt), Norway (Ho:YAG) ASSP’03 (E.Lippert et al., TOPS Vol.83, 292 (2003))
  - BAE Systems (Ho:YAG)
  - Q-Peak (Ho:YLF) ASSP’05
Ho:YLF vs Ho:YAG

- **Ho:YLF**
  - Long upper laser level lifetime ~ 15 ms
  - Higher emission cross-section
  - Naturally birefringent material
  - Low dn/dT → weak thermal lensing
  - ~5% quantum defect

- **Ho:YAG**
  - Isotropic
  - Lifetime \( (5I_1) \) 7 ms
  - Strong thermal lensing
  - Excellent thermo-mechanical properties
  - ~10% quantum defect
Ho:YLF – Absorption/ Emission

Cross-section determination - reciprocity method:

\[ \sigma_{em}(\nu) = \sigma_{abs}(\nu) \left( \frac{Z_l}{Z_u} \right) \exp \left[ \frac{(E_{ZL} - h \nu)}{kT} \right] \]

(Following S.A.Payne et al. IEEE J. of QE, 28, 2619-2630 (1992)).
Ho:YLF – Calculated gain ($\pi$) vs inverted fraction
Q-Peak’ Ho-laser development

2001
• Tunable Tm:YLF laser (>15 W )

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

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

2006
• Single Ho-crystal oscillator followed by three amplifiers pumped with two Tm:fiber lasers (~230 W total power)
Q-Peak’ prior results:
Pumping Ho:YLF with Tm:YLF laser

\[ \text{Absorption coefficient, cm}^{-1} \]

- **2.0\% Ho:YLF**

\[ \text{Wavelength, nm} \]
Q-Peak’ prior results:
Experimental Set-Up – Tm:YLF Laser

- Dual-Gain Module oscillator
- Beam quality: $M^2 \sim 1.05 \times 7$
- Wavelength tuning with BRF element
  - Alternative: Volume Bragg Grating reflector
- Average power (CW) > 30 W at 1940 nm
Q-Peak’ Prior Results:
End-pumped single-crystal Ho:YLF laser

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

DM – Dichroic Mirror,
AOM – Acousto-Optic Modulator,
OC – Output Coupler,
HR – High Reflector
Scaling of Ho-laser: Tm-pump source

- 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.ipgphotonics.com)

<table>
<thead>
<tr>
<th>Operation regime</th>
<th>CW</th>
</tr>
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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>
</tr>
<tr>
<td>Polarization:</td>
<td>Random</td>
</tr>
<tr>
<td>Linewidth</td>
<td>≤ 2 nm</td>
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</tbody>
</table>
Schematic layout of the double-crystal end-pumped Ho:YLF laser

DM – Dichroic Mirror,
AOM – Acousto-Optic Modulator,
OC – Output Coupler,
HR – High Reflector
Ho:YLF Laser – Power output

Mode size (dia):
- \( w_0 = 0.8 \text{ mm} \)
- \( w_1 = 1.0 \text{ mm} \)
- \( w_2 = 1.3 \text{ mm} \)

42% slope efficiency

"Tight" focusing (\( w_0 \))
"Moderate" focusing (\( w_1 \))
"Loose" focusing (\( w_2 \))

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Ho:YLF Laser – Pulse energy

Mode size (dia):
w1 = 1.0 mm
w2 = 1.3 mm

"Moderate" focusing

"Loose" focusing

28 ns
20 ns
17 ns
22 ns
32 ns
28 ns
32 ns
Current work: Specific objectives

Our approach for Tm-pumped Ho-laser:
- Tm-pump: CW Tm-fiber lasers
- Ho-laser: Ho:YLF oscillator with AO Q-switching
- Ho-Amplifiers: Single-pass
Tm:fiber laser pumped single-crystal Ho:YLF laser

DM – Dichroic Mirror,
AOM – Acousto-Optic Modulator,
OC – Output Coupler,
HR – High Reflector
Ho:YLF Master Oscillator

![Graph showing the relationship between input power and energy per pulse for 0.5 kHz and 1 kHz operations.]
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

<table>
<thead>
<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>
</tr>
</thead>
<tbody>
<tr>
<td>Q-Peak</td>
<td>0.3</td>
<td>0.45</td>
<td>2.9</td>
<td>195</td>
</tr>
<tr>
<td>ORC</td>
<td>0.8</td>
<td>0.23</td>
<td>54</td>
<td>3600</td>
</tr>
<tr>
<td>BAE</td>
<td>0.85</td>
<td>0.28</td>
<td>50</td>
<td>3340</td>
</tr>
</tbody>
</table>
Conclusions

Development of an efficient 2-um Ho:YLF MOPA pumped with cw-Tm-fiber-lasers:

- Scalable (modular) Ho:YLF MOPA configuration
  - Highest (to the best of our knowledge) CW output of 113 W
  - Efficient Q-switched operation (> 115 mJ per pulse)
- Repetition rates in wide range (Hz to kHz), particularly, in 500-1000 Hz range
- High beam quality (TEM$_{00}$ beam)

Future work:

- Optimize Ho-amplifiers
- Test complete Ho-MOPA in QS regime
- Pump the OPO
We would like to thank:

- Lockheed-Martin Center for Laser Ultrasonics for continuous support of our work
- Dr. Valentin Gapontsev for sharing his vision on the progress of fiber lasers in general, and Tm:fiber lasers in particular.
- Dr. Denis Gapontsev and Dr. Nikolai Platonov for fruitful technical discussions
- All our vendors who provided crystals, optics and coatings