High-power, high-energy, high-repetition-rate 2050-nm Ho:YLF laser

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Outline

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- Previous Results
- Ho-properties – brief overview
- Q-Peak’ Previous Results
- Tm:fiber Laser - Details
- Ho:YLF Laser – Details
- Conclusions
Motivation

- Development of a 2-um laser source:
  - High-energy (> 200 mJ)
  - High repetition rate (200-1000 Hz)
  - High beam quality ($\text{TEM}_{00}$)

- Immediate applications:
  - Pump source for OPOs
  - Lidar
  - Medical, industrial, military
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 or Ho:YLF, have a large enough gain cross-section for effective high-energy operation.

- Ho:YAG $\sigma_{em} \approx 1 \times 10^{-20}$ cm$^2$
- Ho:YLF $\sigma_{em} \approx 2 \times 10^{-20}$ cm$^2$
References on resonantly pumped Ho lasers


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 the availability of high-power Tm-lasers
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 \sim 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)
  - FFI (Forsvarets forskningsinstitutt), Norway (Ho:YAG)
  - NASA (Ho:YLF)
  - BAE Systems (Ho:YAG)
Ho:YLF vs Ho:YAG

Why 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 \(^{5I_7}\) 7 ms
- Strong thermal lensing
- Excellent thermo-mechanical properties
- ~10% quantum defect
Ho:YLF - Energy level diagram
Theoretical model

Cross-section determination - reciprocity method:

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

(Based on S.A.Payne et al. IEEE J. of QE, 28, 2619-2630 (1992)).

The net gain coefficient:

\[ g(\nu) = N \left[ p \sigma_{em}(\nu) - (1-p) \sigma_{abs}(\nu) \right] \]

Definitions:

- \( Z_p, Z_u \) – partition functions for upper (u) and lower (l) states,
- \( E_{ZL} \) – zero-“phonon” line.
- \( p \) – inversion fraction,
- \( N \) – Ho\(^{3+}\) concentration

Table. Values for 0.5\% Ho:YLF used in the calculations

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<table>
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<tr>
<td>( \frac{Z_l}{Z_u} )</td>
<td>0.81</td>
</tr>
<tr>
<td>( E_{ZL} )</td>
<td>5153 cm(^{-1})</td>
</tr>
<tr>
<td>( N )</td>
<td>7x10(^{19}) cm(^{-3})</td>
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Ho:YLF – Absorption/ Emission

![Graph showing absorption and emission cross-sections as a function of wavelength. Peaks indicate absorption and emission events.]

- Abs./Emiss. cross-section, cm²
- Wavelength, nm
- Pump
- Lasing

Abs./Emiss. cross-section, cm²
Wavelength, nm

 SPIE’05
Ho:YLF – Calculated gain ($\pi$) vs inverted fraction
Q-Peak’ prior results:
Pumping Ho:YLF with Tm:YLF laser

![Graph showing absorption coefficient vs. wavelength for Ho:YLF and Tm-tuning.](image-url)
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:
Tm:YLF–Laser with a Bragg reflector

Slope efficiency 30%

Slope efficiency 30%
Q-Peak’ Prior Results:
End-pumped Ho:YLF laser

DM – Dichroic Mirror,
AOM – Acousto-Optic Modulator,
OC – Output Coupler,
HR – High Reflector
Q-Peak’ prior results:
Ho:YLF laser operation ($\text{TEM}_{oo}$)

- 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
Current work: Specific objectives

Our approach for Tm-pumped Ho-laser:

- **Tm-pump:** CW Tm-fiber laser
- **Ho-laser:** Ho:YLF with AO Q-switching

大方のことをまず行うこと:
- 定義するTm-fiber laser pump source

![Diagram of laser system](image-url)
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
Tm-laser requirements and characteristics

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>Specification</th>
<th>Value</th>
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<tr>
<td>Operation regime</td>
<td>CW</td>
</tr>
<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>
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<tr>
<td>Linewidth</td>
<td>≤ 2 nm</td>
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Schematic layout of the end-pumped Ho:YLF laser

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

Mode size (dia):
$w = 1.0 \text{ mm}$
Ho:YLF Laser – Power output

Mode size (dia):
w0 = 0.8 mm
w1 = 1.0 mm
w2 = 1.3 mm

42% slope efficiency

"Tight" focusing (w0)
"Moderate" focusing (w1)
"Loose" focusing (w2)
Ho:YLF Laser – Pulse energy

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

"Moderate" focusing
- 17 ns
- 22 ns
- 28 ns

"Loose" focusing
- 20 ns
- 32 ns

Total Tm-pump power, W
Ho:YLF pulse energy, mJ
Conclusions

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

- Highest (to the best of our knowledge) CW output of 43 W
- Efficient Q-switched operation (up to 45 mJ per pulse)
- Repetition rates in wide range (Hz to kHz), particularly, in 100-1000 Hz
- High beam quality (TEM\textsubscript{00} beam)

Future work:

- Optimize Ho-oscillator
- Add Ho-amplifier modules