High-energy, kHz-rate, picosecond, 2-µm laser pump source for mid-IR nonlinear optical devices

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Outline

- Objectives
- 2-um system concept
- Prior art
- Ho:YLF spectroscopic properties and modeling
- Experimental details
  - Ho:YLF mode-locked osc
  - Ho:YLF regenerative amplifier
  - Ho:YLF single-pass amplifier
- Conclusions
Objectives

Application:

- Development of a CPA, high-energy 2-um-laser source as a pump for mid-IR parametric devices

Targeted specifications:

- Pulse energies >50 mJ
- Repetition rate 1-2 kHz
- Pulse duration of 1-500 ps
- High-beam quality
CPA Ho-MOPA concept

**Key objectives:**
- Define optimum system configuration to achieve energy/pulse rate targets
  - Seed osc and pulse stretching/compression techniques relatively well developed
  - Emphasis on the amplifier development
- Regenerative amplifier
- Power amplifier stage(s)

**Possible amplifier alternatives:**
- Fiber amplifier?
- Bulk Ho-medium?
- This work: High-gain, bulk Ho:YLF laser amplifier
Prior Art: Q-Peak’s **nanosecond** Ho:YLF MOPAs

**Tm-pump #1**
~120 W at 1940 nm

**Osc/ Amp #1**

**Tm-pump #2**
~120 W at 1940 nm

**Amp #2**

**Tm-pump #3**
~120 W at 1940 nm

**Amp #3**

**Typical pulsewidth 20-25 ns (10-250 ns – range)**

<table>
<thead>
<tr>
<th>Ho-stage/ Regime</th>
<th>CW</th>
<th>100 Hz</th>
<th>500 Hz</th>
<th>1000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Osc/Amp #1</td>
<td>39 W</td>
<td>55 mJ</td>
<td>50 mJ</td>
<td>33 mJ</td>
</tr>
<tr>
<td>Amp#2</td>
<td>76 W</td>
<td>110 mJ</td>
<td>95 mJ</td>
<td>68 mJ</td>
</tr>
<tr>
<td>Amp#3</td>
<td>115 W</td>
<td>170 mJ</td>
<td>140 mJ</td>
<td>105 mJ</td>
</tr>
<tr>
<td>Pump %</td>
<td>100%</td>
<td>70%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

**Tm-fiber laser TLR-120-1940**
IPG Photonics
www.ipgphotonics.com

**Operation regime**

<table>
<thead>
<tr>
<th></th>
<th>CW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Profile</td>
<td>TEMoo</td>
</tr>
<tr>
<td>Output power</td>
<td>≥ 120 W</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1940 nm</td>
</tr>
<tr>
<td>Polarization</td>
<td>Random</td>
</tr>
<tr>
<td>Linewidth</td>
<td>≤ 2 nm</td>
</tr>
</tbody>
</table>

Prior art: High gain Ho:YLF amplifiers

Recent reported results re high-gain Ho-amplifiers:

- **Dergachev, ASSP 2009**
  - 23-dB Ho:YLF double-pass amplifier
  - 10 mW seed / 2 W output at 2.05 um
  - single-frequency/broadband/pulsed

  - 5-pass Ho:YLF amplifier for 2-um tail of Er:fiber comb source (av. 30 dB gain in 2.05-2.07 um range)
  - 50-mm long, Brewster-cut Ho:YLF
  - 1.6-W comb in 2.05-2.07 um
  - 20-W Tm:fiber source

- **Dergachev, ASSP 2012**
  - **45-dB, Compact, Single-Frequency, 2-µm Amplifier**
  - 0.12 mW seed / 4.5 W output at 2.05 um
  - single-frequency/broadband/pulsed
Recent work: Ho:YAG CPA

Recent work:


- CPA Ho:YAG
- 3 mJ, 5 kHz, ~250 ps
- 0.5 ps - after compression
# Ho-Laser Media: YLF vs YAG

## Host parameters

<table>
<thead>
<tr>
<th>Material type</th>
<th>Ho:YLF</th>
<th>Ho:YAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transparency range (undoped), µm</td>
<td>0.18-6.7</td>
<td>0.21-5.3</td>
</tr>
<tr>
<td>Thermal conductivity, Wm/K</td>
<td>6.3</td>
<td>13</td>
</tr>
<tr>
<td>Refractive index (at 2 µm)</td>
<td>1.44 ($n_o$) 1.46 ($n_e$)</td>
<td>1.80</td>
</tr>
<tr>
<td>dn/dT (at 1.0 µm)</td>
<td>-4.3x10^{-6}(llc),-2.0x10^{-6}(lc)</td>
<td>7.3x10^{-6}/K</td>
</tr>
<tr>
<td>Nonlinear refractive index ($n_2$), m²/W</td>
<td>1.7x10^{-20}</td>
<td>8.1x10^{-20}</td>
</tr>
<tr>
<td>Bulk damage threshold, GW/cm²</td>
<td>18.9 (at 4.6 ns)*</td>
<td>10.1 (at 4.6 ns)*</td>
</tr>
<tr>
<td>Critical power (self-focusing), MW</td>
<td>24**</td>
<td>5.3**</td>
</tr>
</tbody>
</table>

## Ho-doped medium

| λ_{abs}, nm | 1940 | 1907 |
| λ_{em}, nm | 2051 | 2098 |
| σ_{em}, cm² | 1.84x10^{-20} | 0.98x10^{-20} |
| Quantum defect (1-λ_{abs}/λ_{em}), % | 5.4 | 9.1 |
| t_{em}, ms | 15 | 7 |

## Notes:
- **Critical power for self-focusing is calculated as $P_{cr} = \alpha(\lambda^2/4\pi n n_2)$, where $\alpha = 1.8962$ for a Gaussian beam.
- Ho:YAG data from S.A. Payne et al. IEEE J. of QE, 28, 2619-2630 (1992)).
Ho:YLF – Absorption/ Emission ($E||c$)

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 (||c) vs wavelength (various inverted fractions)

The net gain coefficient:

\[ g(\nu) = N \left[ p \sigma_{em}(\nu) - (1-p) \sigma_{abs}(\nu) \right] \]
Relatively high-brightness sources are required

- Efficient GSD laser pumping requires high optical density $\alpha L \gg 1$
- The use of a Tm-fiber laser with diffraction-limited beam quality is essential to provide long, collimated gain regions enabling high gain operation of the bulk Ho-amplifier

- 1850-1950 nm wavelength range
- High average power up to 150 W – commercial products
- Possible alternatives:
  - Diode-pumped Tm-bulk solid state lasers
  - Direct diode-pumping (at ~1.9 um) – not too bright!

This work: Tm:fiber lasers (IPG Photonics):
- TEM$_{00}$
- < 20 W
- 1940 nm
- Linearly polarized
- < 2 nm linewidth
Mode-locked oscillator:
- 0.5% Ho:YLF, 30-mm long, wedged
- AR/AR-coated at 1940/2050 nm
- TE-cooled at 20°C
- Active mode-locking (TeO$_2$ AOM, 41 MHz)
- Resonator length: 184 cm
- Tm-pump power up to 15W
- Output: up to 4W (~38% slope)
- 81 MHz
- 250-300 ps
Ho:YLF regenerative amplifier

Regen amp:
- 0.5 % Ho:YLF, 40-mm long, wedged
- AR/AR-coated at 1940/2050 nm
- TE-cooled at 20C
- EO: RTP 20-mm long, ¼-wave voltage
- Resonator length: ~184 cm
- Triggering off RF signal to AOM
- Rate: 1-10 kHz
- Gate width ~165-200 ns (~14-17 round trips)
- Tm-pump power up to 15W
- Output: Typical av. power 1-2 W
- ~1.7 mJ at 1 kHz

Regen target: >1 mJ at 1 kHz (!!!)
Ho:YLF single-pass, 2-xtal amplifier

2-xtal power amp:
- Single pass
- 0.5 % Ho:YLF, 30-70-mm long, wedged
- AR/AR-coated at 1940/2050 nm
- TE-cooled at 20°C
- Adapted for 2-beam pumping with pol.-split unpol. fiber laser
- Tm-pump power up to 75W
Ho:YLF single-pass, 2-xtal amplifier - Model

**Model:**
- 1 mJ / 1 kHz / 300 ps seed
- Fixed pump power (60W)
- Vary beam size for the seed and pump beams

**Experiment:**
- 1 mJ (1 kHz) - In
- ~11 mJ - Out
- ~300 ps
- 1.3-mm dia
- ~2.5 GW/cm²

**2-xtal power amp:**
- Single pass
- 0.5 % Ho:YLF, 70-mm long – each
- Pump power 60W – Total
Ho:YLF single-pass, 2-xtal amplifier

At pulse rates $\geq$ 5 kHz, average power is the same as in CW.

- **1 kHz** (11 mJ): Seed input: 0.2 mJ, $\sim$300 ps
- **5 kHz** (2.6 mJ): Seed input: 0.1 mJ, $\sim$300 ps
- **10 kHz** (1.4 mJ): Seed input: 0.1 mJ, $\sim$300 ps

Average power:
- $\sim$11 W (1 kHz)
- $\sim$13 W (≥5 kHz)
Conclusions

Ho:YLF regenerative amplifier:
• Up to 1.7 mJ at 1 kHz (nominal regime)
• 1-10 kHz – operating pulse rate
• ~300 ps

Ho:YLF power amplifier:
• ~11 mJ at 1 kHz (nominal regime)
• Further scaling to ~20 mJ is straightforward

Concerns:
• Damage limitations -> laser damage tests of Ho:YLF at 2 um
• Fine-tuning of the power amp design

Further work:
• Operation with chirped-pulse seed
• Spectral shaping
• Scaling to reach ~50 mJ target -> additional amp stage(s)
• Compression of amplified pulses
• Packaging