2 µm Fiber Lasers

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ISPD1
June 26, 2013
Introduction

Review of near IR to mid IR fiber lasers

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<table>
<thead>
<tr>
<th>Dopant(s)</th>
<th>Host glass</th>
<th>Pump λ (μm)</th>
<th>Laser λ (μm)</th>
<th>Transition</th>
<th>Output power (W)</th>
<th>Slope efficiency (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Er³⁺, Yb³⁺</td>
<td>Silicate</td>
<td>0.975</td>
<td>1.5</td>
<td>⁴I₁₃/₂ → ⁴I₅/₂</td>
<td>297</td>
<td>19</td>
<td>21</td>
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<tr>
<td>Tm³⁺, Ho³⁺</td>
<td>ZBLAN</td>
<td>0.792</td>
<td>1.94</td>
<td>³F₄ → ³H₆</td>
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<tr>
<td>Tm³⁺</td>
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<td>³F₄ → ³H₆</td>
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<td>22</td>
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<tr>
<td>Tm³⁺, Ho³⁺</td>
<td>Silicate</td>
<td>0.793</td>
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<td>⁵I₇ → ⁵I₈</td>
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<td>42</td>
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<tr>
<td>Ho³⁺</td>
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<tr>
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<tr>
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<td>13</td>
<td>24</td>
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<tr>
<td>Ho³⁺, Pr³⁺</td>
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<td>2.86</td>
<td>⁵I₆ → ⁵I₇</td>
<td>2.5</td>
<td>29</td>
<td>25</td>
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<tr>
<td>Dy³⁺</td>
<td>ZBLAN</td>
<td>1.1</td>
<td>2.9</td>
<td>⁴H₁₃/₂ → ⁴H₅/₂</td>
<td>0.275</td>
<td>4.5</td>
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<tr>
<td>Ho³⁺</td>
<td>ZBLAN</td>
<td>1.15</td>
<td>3.002</td>
<td>⁵I₆ → ⁵I₇</td>
<td>0.77</td>
<td>12.4</td>
<td>26</td>
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<tr>
<td>Ho³⁺</td>
<td>ZBLAN</td>
<td>0.532</td>
<td>3.22</td>
<td>⁵S₂ → ⁵F₅</td>
<td>0.001</td>
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<td>27</td>
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<tr>
<td>Er³⁺</td>
<td>ZBLAN</td>
<td>0.653</td>
<td>3.45</td>
<td>⁴F₉/₂ → ⁴I₉/₂</td>
<td>0.008</td>
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<tr>
<td>Ho³⁺</td>
<td>ZBLAN</td>
<td>0.89</td>
<td>3.95</td>
<td>⁵I₅ → ⁵I₆</td>
<td>0.001</td>
<td>3.7</td>
<td>29</td>
</tr>
</tbody>
</table>

Absorption Spectra of Selected Gases

Absorption (Arb. Units)

H_{2}O

CO_{2}

CH_{4}

Wavelength (µm)

Thulium window (1.8 – 2.1 µm)

HITRAN2008 line spectrum(\url{http://www.spectralcalc.com})
Outline

• Review of 2 µm fiber laser development
  - CW
  - Pulsed

• Application
  - Nonlinear pump
High power, single frequency

- 790 nm pumping with 54% slope efficiency
- Non-PM LMA Tm fiber 25/400 with 0.08 NA
- $M^2 = 1.05$ at 608 W

High power, single frequency

- <5 MHz linewidth maintained with <0.4% of total power in ASE
- High power single-mode and single-frequency output achieved by suppression of SBS
- Low phase noise and high quality output ideal for coherent beam combining

All-fiber 1 kW Tm Laser

The pump is 6 Tm:fiber lasers at 1.95 μm (160-180 W each)
Tm:fiber 15 μm core, 0.1 NA, 25 μm pedestal

Ho:fiber 18 μm core, 0.08 NA, 112 μm octagonal cladding
V-parameter 2.2 ensures robust single-mode output

Initially ~50% slope efficiency

Tm:fiber Tuning Range


- 216 W maximum output
- 60% amplifier optical-to-optical efficiency
- 790 nm diode pumping
- >200 W from 1927-2097 nm
- <200 pm linewidth
- Nearly diffraction-limited

Tm:fiber SBC Results

MOPA 1: 2046 nm, 87 W
MOPA 2: 2040 nm, 99 W
MOPA 3: 2035 nm, 98 W

89% combining efficiency, 35% total optical-to-optical efficiency
Incident Power 284 W, combined power 253 W
• Tm and Ho fiber development have achieved 1 kW and 400 W average power respectively with nearly diffraction-limited beam quality
• Component availability and performance improving
• Power scaling is primarily limited by heat, in particular Ho:fiber is far from theoretical efficiency
• Doped glass chemistry is a challenge
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Gain switched nanosecond

Ho:fiber output 16 µJ energy, 85 ns duration at 600 kHz >60% slope efficiency, $M^2 < 1.1$


This method can be used to produce 10 ns pulses directly without the need for active modulators at 2 µm

Narrow linewidth nanosecond Tm:fiber lasers

Primarily for LIDAR applications, several efforts to develop high peak power Tm:fiber “single-frequency” sources


Q. Fang et al., "High power and high energy monolithic single frequency 2 μm nanosecond pulsed fiber laser by using large core Tm-doped germanate fibers: experiment and modeling," Opt. Ex. 20, 16410 (2012)
Comparison of Tm-doped LMA Fibers

<table>
<thead>
<tr>
<th>Fiber</th>
<th>LMA 25/400</th>
<th>Flexible PCF 50/250</th>
<th>PCF Rod 80/220</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td>3 m</td>
<td>3 m</td>
<td>1.5 m</td>
</tr>
<tr>
<td><strong>Mode field diameter</strong></td>
<td>23 µm</td>
<td>36 µm</td>
<td>56 µm</td>
</tr>
<tr>
<td><strong>Numerical aperture</strong></td>
<td>0.1</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>Mode field area</strong></td>
<td>~400 µm²</td>
<td>~1000 µm²</td>
<td>~2500 µm²</td>
</tr>
</tbody>
</table>

**CW lasing in Tm:PCF**

**Q-switched Tm:PCF oscillator**

**CW lasing in Tm:PCF rod**
Comparison of Tm-doped LMA Fibers

C.C.C. Willis et al., “High energy Q-switched Tm$^{3+}$-doped polarization maintaining silica fiber laser,” Photonics West 2010, paper 75801F

• The percentage of usable output reduces from 80% to <60% starting with pulse energies >100 µJ and a minimum pulse duration of 150 ns
• No such degradation occurs using PCF, enabling energy scaling to 435 µJ energy with 49 ns pulse duration

P. Kadwani et al., “Comparison of higher-order mode suppression and Q-switched laser performance in thulium-doped large mode area and photonic crystal fibers”, Opt. Exp. 20, 24295 (2012)
Recent modal characterization measurements confirm Tm-doped PCFs offer significantly larger mode area and reduced higher-order mode content.

*This work done with Prof. Axel Schülzgen and Clemence Jollivet*

P. Kadwani et al., “Comparison of higher-order mode suppression and Q-switched laser performance in thulium-doped large mode area and photonic crystal fibers”, Opt. Exp. 20, 24295 (2012)
Nanosecond Peak Power Scaling

Amplification to >890 kW with no evidence of nonlinear pulse degradation

C. Gaida et al., “Amplification of nanosecond pulses to megawatt peak power levels in Tm\textsuperscript{3+}-doped photonic crystal fiber rod”, Opt. Lett. 38, 691 (2013)

>50 W CW in Tm:LPF


>2.4 mJ, 33 W in Tm:LPF

Seed pulses generated by a gain switched InGaAs/InP diode

Maximum peak power of 100 kW: 3.5 µJ, 33 ps pulse at 2 MHz

Further scaling claimed to be limited by modal instability (MI)

After spectral filtering:
- 3 nJ pulse energy
- ~150 fs pulse duration
- ~30 nm (FWHM) spectral width
- Tuning range 1980 – 2100 nm

Tm:fiber CPA with CBG

Pulse stretching to 160 ps and recompression using a Chirped Bragg Grating (CBG) from OptiGrate

\[ \Delta \lambda = 30 \text{ nm (FWHM)} \]
\[ \lambda_{\text{cen}} = 2020 \text{ nm} \]
Amplified to >5 W at 60 MHz


37 \mu J in 910 fs

P. Wan et al., “High pulse energy 2 \mu m femtosecond fiber laser”, Opt. Ex.21,1798 (2013)
Utilizing the Bandwidth

Normal GVD stretcher fiber
Pulse duration \( \sim 40 \) ps
Similarton-like pulse broadening
from 29 to 60 nm

Center Wavelength 2020 nm
Average Power 12.8 W
182 nJ uncompressed, 60 nm Bandwidth
In the last two years, the development of CPA systems has accelerated greatly -

> MW peak power, <100 fs

Nanosecond system development is maturing -

MW peak power, 1-10 ns range

Picosecond laser development has lagged behind CPA and nanosecond, but is rapidly emerging

100 kW peak power, ~30 ps
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Another entire area of application for 2 µm fiber laser is in telecommunication, using HC-PBF

Nanosecond OPO

Simple flat-flat ZGP OPO cavity pumped by high peak power Tm:PCF based MOPA

The combination of Tm:fiber frequency comb and nonlinear conversion (OPO enhancement cavity) offers new tools mid-IR spectroscopy.

### Laser
- Pulse duration: 450 fs
- Peak power: 9.6 kW

### Sample
- Length: 6.8 cm
- Minimum core: 250 nm
- Core: $\text{As}_2\text{Se}_{1.5}\text{S}_{1.5}$
- Cladding: $\text{As}_2\text{S}_3$

**In tellurite fiber**

**In chalcogenide fiber**

This fiber supplied by Profs. Heike Ebendorff-Heidepriem and Tanya Monro, Univ. of Adelaide

This work done in collaboration with Prof. Ayman Abouraddy and Soroush Shabahang
• 2 µm fiber lasers have proven a unique source for pumping nonlinear processes particularly the generation of mid-IR

• Excellent beam quality and high average power are readily achievable

• Additional processes will be enabled by the continued advance in Tm: and Ho: fiber sources
Final Questions

- CW – How to improve dopant material to achieve high efficiency?
- Pulsed – Can 2 µm fiber lasers take advantage of lower nonlinearity to exceed Yb:fiber lasers in peak power?
- Nonlinear pump – Can 2 µm fiber lasers compete with the peak power from Ho:solid-state systems?
Thank You!
The 2 μm wavelength is attractive for polymer welding

Si “Backside” Machining

On target:
Maximum energy $E = 200 \, \mu J$
Minimum diameter $d = 10 \, \mu m$
Maximum fluence $F = 255 \, J/cm^2$

Target:
500 $\mu m$ thick, DSP un-doped Si wafers

[Diagram of laser system with labels for Tm:fiber MOPA system, Shutter, Mirror, Wafer target, 7.5 mm asph. lens, Vertical Rail, 3D motorized motion control stage]
Si “Backside” Machining

Front and backside machining look very different, and require very different powers!

Front
(200 mW, 1 mm/s, focus 0 µm)

Backside
(200 mW, 1 mm/s, focus in air ~400 µm)