Power Scaling of Tm:fiber Lasers to the kW Level

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Outline

- Background
- Fundamentals of Tm:silica fiber lasers
- Fiber laser setup and results

Support:

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Technical work:

Q-Peak: Glen Rines, Evgueni Slobodtchikov, Kevin Wall,
Nufern: Gavin Frith, Bryce Samson, Adrian Carter
Relative eye safety is obtained for > 1400-nm wavelengths.

Retinal focusing can increase the power density by $10^5$. 
Rare-earth laser transitions can provide eyesafe wavelengths in fibers.
Tm-ion cross relaxation allows excitation of two upper laser levels for one pump photon.
Prior work with Tm:YAG lasers


Recent advances in Tm-doped fiber-laser efficiencies show levels approaching Yb fibers.
Fundamentals of Tm:silica fiber lasers
Absorption and emission cross sections for Tm:silica

Absorption: Nufern
Emission: Walsh (NASA)
We define the inversion fraction as:

\[ F = \frac{N_2}{N_2 + N_1}, \]

where \( N_1 \) and \( N_2 \) are the inversion densities for the lower and upper Tm:silica laser levels.

The net gain (or loss) cross section \( \sigma(\lambda) \) in the fiber as a function of wavelength, \( \lambda \), is given by the relation:

\[ \sigma (\lambda) = F \ \sigma_e (\lambda) - (1-F) \ \sigma_a (\lambda), \]

where \( \sigma_e (\lambda) \) and \( \sigma_a (\lambda) \) are the emission and absorption cross sections. The gain or loss coefficient is \( \sigma (\lambda) \) multiplied by the concentration of active ions.
Plot of net gain cross section in Tm:silica vs. inversion fraction

Data on emission cross section from Walsh and absorption cross sections from Nufern
Tm:silica gain at low inversions

Net gain cross sections needed for 5-m fiber length, with gain of 25
Polished preforms and sample holder
Absorbance data from Lambda 9 measurements

Result:
LO: 2.03-2.36 wt% (Tm$_2$O$_3$)
HI: 2.47-2.87 wt%
The photodarkening issue has not appeared in pumping highly doped fibers at 790 nm.

Dynamics measurements of Tm:silica

Pump at ~800 nm

Cross Relaxation

Multiphonon Emission

Laser Transition 1950-2050 nm

800-nm emission
Decay data for $^3F_4$ (upper laser) level shows two-lifetime dynamics.

- LO data broadband
- Double exponential fit
- 633 usec lifetime
- 281 usec lifetime
Initial portion of $^3F_4$ signal shows feeding from pumped level.
800-nm fluorescence provides data on cross-relaxation efficiency.

Assuming 45 usec lifetime for low Tm doping, efficiency of cross relaxation:
- 74% for LO
- 80% for HI

Time (microseconds)

Signal level (arb. units)

Decay in tail: 24.3 usec (LO), 21.0 usec (HI)

5.6 usec to 1/e

7.9 usec to 1/e
Fiber laser setup and results
Approach to scaling follows on work done by SOTON on Yb:fiber lasers

- **Diode stack @975 nm, 1.2 kW**
  - HT @975 nm
  - HR @~1.1 µm

- **Double-clad Yb-doped fibre**
  - Signal output @~1.1 µm
  - HT @975 nm
  - HR @~1.1 µm

- **Diode stack @975 nm, 0.6 kW**
  - HT @975 nm
  - HR @~1.1 µm

Measured data:

- **Slope efficiency: 83%**

- **Linear fit**

- **Signal power [kW]** vs. **Launched pump power [kW]**
Details of the 790-nm pump band (2 wt. % Tm) showing broad absorption
350-W Laserline pump laser (1 of 2)

- Rack unit with diodes, power supply and cooler
- 5-m delivery fiber
- 1:1 lens focusing optics
- High-power connector
Pump laser wavelengths were 795 nm at full power.

Spectral emission data for pump lasers #1 and #2, respectively at a drive current of 55A, approximately 350 W of power output.
Q-Peak fiber-laser testbed

Active fiber coil

Heat sink

2.5-cm R concave surface
HR at 2050 nm
HT at 790 nm

Dichroic mirror
HR at 2050 nm
HT at 790 nm

Pump Laser A

Pump Laser B

793-nm pump
400-um, 0.2 NA fiber delivery

Single-ended pump

Focusing head

Focusing head

Clamp

Clamp

Power meter

2050 nm output
### Characteristics of Nufern-supplied fibers

<table>
<thead>
<tr>
<th>Fiber ID</th>
<th>MM-TDF-20/400-LO</th>
<th>MM-TDF-20/400-Hi</th>
<th>LMA-20/35/400-Hi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core diameter</td>
<td>17-23 µm</td>
<td>17-23 µm</td>
<td>17-23 µm</td>
</tr>
<tr>
<td>Clad diameter</td>
<td>385-415 µm</td>
<td>385-415 µm</td>
<td>385-415 µm</td>
</tr>
<tr>
<td>Core NA (effective)</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Cladding NA</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
</tr>
<tr>
<td>V value at 2 µm</td>
<td>&gt;6</td>
<td>&gt;6</td>
<td>&lt;4</td>
</tr>
<tr>
<td># of modes (2 µm)</td>
<td>7</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Cladding absorption (795nm)</td>
<td>~2dB/m</td>
<td>~2.6dB/m</td>
<td>~2.6dB/m</td>
</tr>
<tr>
<td>Tm-concentration</td>
<td>2.7 wt%</td>
<td>3.5 wt%</td>
<td>3.5 wt%</td>
</tr>
<tr>
<td>Cladding Shape</td>
<td>Octagon</td>
<td>Octagon</td>
<td>Octagon</td>
</tr>
</tbody>
</table>

At 790.1 nm (2.5-nm linewidth) we measured 1.09 dB/m for LO fiber (10-m length) and 1.54 dB/m for HI fiber (7-m length)
Summary of highest-power LO and HI Tm:fiber lasers

- **LO fiber data**
- **HI fiber data**

- **LO linear fit**

- 46.3% slope

Launched pump power (W) vs. Output power (W) graph.
Fiber assembly: 5-m length of Tm-doped fiber (3), with two undoped, 3-m-long fibers (1) fusion-spliced (2) to the ends of the doped fiber.

Gain fiber: LMA HI2
Cores: 25 µm in diameter, NA: 0.08.
Pump claddings: 400-µm in diameter, octagonal cross section
Pump attenuation: 2.9 dB/m
Slope efficiency data, corrected for absorbed power, is 71.7% in good agreement with the value of 69.8% calculated by spectroscopy. The pump quantum efficiency is 1.84.
LMA HI2 fiber laser beam quality close to D.L.

- Horiz. raw data
- Vert. raw data
- Horiz. processed data
- Vert. processed data

Beam width (µm)

Horiz. axis, $M_x^2 = 1.21$
Vert. axis, $M_y^2 = 1.16$
The laser was pumped from one end with 47 W, and had a 600g/mm Littrow grating as an end mirror.
Next: Scale the Tm-doped fiber laser to 1 kW

Fiber coupled diode stacks
1000 W at 790 nm, 1000 um 0.22 NA

Double-clad Tm-doped fiber
Cladding 625 um, 0.46 NA
Core 35 um

Signal output @~2 μm

HT @790 nm
HR @~2 μm

HT @790 nm
HR @~2 μm
Rack of pump lasers, 1-kW Q-Peak pump data

Hole for second 1 kW pump

1 kW pump

350 W pumps

86% transmission through fiber (93% maximum with uncoated ends)

Power through undoped fiber MM-GDF-625/35

Power through lens assembly

I/O data from Laserlines 1-kW LDM (S/N 760420)

Current Monitor (V)

Power Output (W)
New world’s record for Tm:fiber power

- **885 W @ 50.7% efficiency**
- **51% slope**
Cutback measurements on 35/625 fiber show absorption to be double exponential.

\[ T = A_s \exp(-\alpha_s L) + A_l \exp(-\alpha_l L) \]

- \( A_s = 0.493 \)
- \( \alpha_s (\text{}/\text{m}) = 1.38 \)
- \( A_l = 0.395 \)
- \( \alpha_l (\text{}/\text{m}) = 0.50 \)
Cutback absorption measurements on 400-um cladding fibers - single exponential absorption

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Nominal doping (%)</th>
<th>Cladding absorption coefficient (/m)</th>
<th>Core absorption coefficient (/m)</th>
<th>Area ratio</th>
<th>Predicted cladding absorption coefficient (/m)</th>
<th>Measured /predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO</td>
<td>2.7</td>
<td>0.292</td>
<td>158</td>
<td>0.00250</td>
<td>0.395</td>
<td>0.74</td>
</tr>
<tr>
<td>LMA-HI1</td>
<td>3.5</td>
<td>0.438</td>
<td>192</td>
<td>0.00250</td>
<td>0.480</td>
<td>0.91</td>
</tr>
<tr>
<td>LMA-HI2</td>
<td>4.5</td>
<td>0.664</td>
<td>247</td>
<td>0.00391</td>
<td>0.965</td>
<td>0.69</td>
</tr>
</tbody>
</table>
Thermal modeling for 200 W/m indicates cladding/buffer temperature well below 100 C

The cladding/buffer interface reaches 100 C sooner for the smaller diameter fiber even with a thinner buffer.

35/625/819 \( P_{\text{critical}} = 382 \) W/m

25/400/550 \( P_{\text{critical}} = 323 \) W/m
Tm-Doped Fiber Lasers: Fundamentals and Power Scaling

Peter F. Moulton, Senior Member, IEEE, Glen A. Rines, Member, IEEE, Evgueni V. Slobodtchikov, Kevin F. Wall, Gavin Frith, Bryce Samson, and Adrian L. G. Carter

Abstract—We describe fundamental measurements of the properties of thulium (Tm)-doped silica and power scaling studies of fiber lasers based on the material. Data on the high-lying Tm: silica energy levels, the first taken to our knowledge, indicate that pumping at 790 nm is unlikely to lead to fiber darkening via multiphoton excitation. Measurement of the cross-relaxation dynamics produces an estimate that, at the doping levels used, as much as 80% of the decay of the Tm level pumped is due to cross relaxation. Using a fiber having a 25-μm-diameter, 0.08 numerical aperture (NA) core, we observed fiber laser efficiencies as high as 64.5% and output powers of 300 W (around 2040 nm) for 500 W of launched pump power, with a nearly diffraction-limited beam. At these efficiencies, the cross-relaxation process was producing 1.8 laser photons per pump photon. We generated 885 W from a multimode laser using a 35-μm, 0.2-NA core fiber and set a new record for Tm-doped fiber laser continuous-wave power.

Index Terms—Fiber lasers, spectroscopy, thulium (Tm) doping.

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Scaling issues for Tm-doped fibers compared to Yb-doped fibers

\[ V = 2\pi \frac{a}{\lambda_o} NA \]

\( V < 2.405 \) for single-mode fiber

\( a \) is core radius, \( \lambda \) is wavelength

Optical damage fluence (dielectric breakdown): scales as \( \lambda \)

Raman gain: scales as \( 1/\lambda \)

Brillouin gain: scales as \( 1/ (\lambda)^2 \times 1/\text{linewidth} \)

**Thus, for the same V parameter, compared to Yb-doped fibers, Tm-doped fibers have:**

- 8 X higher fiber end-facet damage threshold
- 8X higher stimulated Raman scattering threshold
- TBD higher stimulated Brillouin scattering threshold
High-power single-frequency results from NGAS

Gregory D. Goodno, Lewis D. Book, and Joshua E. Rothenberg

SPIE Photonics West January 27, 2009
Applications of high-power Tm-doped fiber lasers

- Directed energy
- IRCM
- Remote Sensing for CBW detection
- Remote Sensing of Global Winds
- Coherent laser radar
- Driver for laser ultrasonics NDT for aircraft parts
- Pump source for mid-IR ultrafast systems
Ho:YLF MOPA chain produces record for hybrid system with Tm:fiber pumps

- **Tm-pump #1**: ~120 W at 1940 nm
- **Osc/Amp #1**:
  - Output power: 39 W, 55 mJ, 50 mJ
- **Amp #2**:
  - Output power: 76 W, 110 mJ, 95 mJ
- **Amp #3**:
  - Output power: 115 W, 170 mJ, 140 mJ

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

**Tm-fiber laser TLR-100-1940**
IPG Photonics
www.ipgphotonics.com

- Operation regime: CW
- Beam Profile: TEM_00
- Output power: ≥ 120 W
- Wavelength: 1940 nm
- Polarization: Random
- Linewidth: ≤ 2 nm
ZGP OPO/OPA layout for 3200-nm generation

Ho-MOPA

BS

Ch. 1
<60 mJ

Ch. 2
<100 mJ

DM1

HR

DM2

DM3

DM4

OPA output

OPA

ZGP 10 mm

Ristra OPO

ZGP 10 mm

ZGP obtained from Inrad
ZGP OPA - various repetition rates

OPA pump beam size remains optimized for max pulse energy of ~100 mJ (100 Hz)
**Cr:ZnSe CPA system based on Tm:fiber pumps**

- **1.9-2.0-µm 5-W PM Tm:fiber CW pump laser**
- **2.5-µm CEP-stabilized Cr:ZnSe femtosecond laser (100 fs, 1 nJ, 100 MHz)**
- **1.94-µm 50-W Tm:fiber CW pump laser**
- **Pulse stretcher 100 fs \(\rightarrow\) 100 ps**
- **2.05-µm Ho:YLF Q-switched pump laser (17 mJ, 1 kHz)**
- **2.5-µm Cr:ZnSe regenerative amplifier (4.5 mJ, 1 kHz)**

**Output:**
- 2.5 µm, 100 fs
- 3 mJ, 1 kHz

**Pulse compressor**
CW Cr:ZnSe laser generates 130 fs pulses at 2530 nm
Conclusions

• Tm:silica fiber lasers may provide power levels and efficiencies approaching that of Yb:silica fibers

• We have measured some fundamental properties of Tm:silica to better understand laser operation

• With a 25/35/400 Tm:silica fiber laser, we generated 301 W, with 60% conversion of launched pump power to laser output

• The laser slope efficiency indicates that each pump photon generates 1.84 laser photons

• With a 35/625 Tm:silica laser we have generated 885 W of power, a new record for this technology.