Power Scaling of High-Efficiency, 
Tm-doped Fiber Lasers

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Q-Peak, Inc.

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Outline

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

Support:

HEL-J TO Contract No. FA9451-06-D-0009

Technical work:

Q-Peak: Evgueni Slobodtchikov, Kevin Wall, Glen Rines
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.
Recent work: efficient, high-power Tm-doped fiber lasers


Also: Nufern, 100 W Tm:silica laser
Ho:YLF MOPA chain produces record for hybrid system with Tm:fiber pumps

<table>
<thead>
<tr>
<th></th>
<th>CW</th>
<th>500 Hz</th>
<th>1000 Hz</th>
</tr>
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<tbody>
<tr>
<td>Master osc</td>
<td>19 W</td>
<td>25 mJ</td>
<td>17 mJ</td>
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<tr>
<td>Amp 1</td>
<td>42 W</td>
<td>55 mJ</td>
<td>38 mJ</td>
</tr>
<tr>
<td>Amp 2</td>
<td>60 W</td>
<td>90 mJ</td>
<td>58 mJ</td>
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<tr>
<td>Amp 3</td>
<td>78 W</td>
<td>115 mJ</td>
<td>73 mJ</td>
</tr>
<tr>
<td>Amp 4</td>
<td>97 W</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Amp 5</td>
<td>113 W</td>
<td>***</td>
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*** work in progress

Used IPG fiber lasers that in-band pumped by Yb, Er fiber lasers and are <10% efficient, overall

Note: IPG has scaled this design to 405 W.
Fundamentals of Tm:silica fiber lasers
Absorption and emission cross sections for Tm:silica

- Absorption: Nufern
- Emission: Walsh (NASA)
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
Result:
LO: 2.03-2.36 wt% (Tm$_2$O$_3$)
HI: 2.47-2.87 wt%
Retiring the photodarkening issue?

Dynamics measurements of Tm:silica

Diagram showing energy levels and transitions:
- Pump at \(-800\) nm
- Cross Relaxation
- Multiphonon Emission
- Laser Transition 1950-2050 nm

800-nm emission
Decay data for $^{3}\text{F}_4$ (upper laser) level shows two-lifetime dynamics.
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

Decay in tail: 24.3 usec (LO), 21.0 usec (HI)
Scaling issues for Tm-doped fibers compared to Yb-doped fibers

\[ V = 2\pi \frac{a}{\lambda_o} NA \quad V < 2.405 \text{ for single-mode fiber} \]

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

- Optical damage fluence (dielectric breakdown): scales as \( l \)
- Raman gain: scales as \( 1/l \)
- Brillouin gain: scales as \( 1/ (l)^2 \times 1/\text{linewidth} \)

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

- 8X higher fiber end-facet damage threshold
- 8X higher stimulated Raman scattering threshold
- TBD higher stimulated Brillouin scattering threshold
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

Diode stack @975 nm, 0.6 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

Slope efficiency: 83%

Graph showing measured and linear fit signal power versus launched pump power.
Details of the 790-nm pump band (2 wt. % Tm)
showing broad absorption
350-W Laserline pump laser (1 of 2)

- 5-m delivery fiber
- Rack unit with diodes, power supply and cooler
- 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

Power meter

Pump Laser A

Pump Laser B

Focusing head

Dichroic mirror

HR at 2050 nm
HT at 790 nm

Dichroic mirror

HR at 2050 nm
HT at 790 nm

Active fiber coil

Meniscus

2.5-cm R concave surface

HR at 2050 nm
HT at 790 nm

Heat sink

Single-ended pump

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

Pump Laser A

Pump Laser B
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
Results with 350-W pump lasers, LMA HI2 fiber

- 59.1% slope
- 61.8% slope
- 64.5% slope
- 59.1% slope

Launched pump power (W) vs. Output power (W) graph
LMA HI2 fiber laser beam quality close to D.L.

Beam width (μm)

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

Horiz. axis, $M_x^2=1.21$
Vert. axis, $M_y^2=1.16$

EP 7290 camera distance (mm)
Tuning of LMA HI2 laser limited on short-wavelength end by high gain

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

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

Power through undoped fiber MM-GDF-625/35

Power through lens assembly

86% transmission through fiber (93% maximum with uncoated ends)
New world’s record for Tm:fiber power

- Output power vs. launched pump power for Fiber 1 and Fiber 2.
- Key data point: 885 W at 50.7% efficiency.
- 51% slope for Fiber 1.
Application to laser accelerators
Motivation

• The maximum energy generated by conventional, microwave-driven electron accelerators is starting to reach a practical limit imposed by size, either in circumference for storage rings, or in length for linear accelerators. The logical evolution for increasing the energy of linear accelerators (or decreasing their size for the same energy) is to increase the acceleration field. By substituting lasers for microwave sources, one can obtain both higher peak powers and also, because of the ability to focus the much more tightly, much smaller beam areas. The net result in increased intensity is that an accelerating field of, say, a 1 TW, 1000-nm laser can exceed that of a 100 MW, 10-cm microwave source by 7 orders-of-magnitude
Design for laser-based electron accelerator

www.slac.stanford.edu/grp/arb/Byer.pdf
Dielectric structure for accelerator

With an index of ~3.5, a good thermal conductivity and availability silicon would appear to be an ideal choice for the dielectric, however its transparency range requires the use of λ~2μm lasers that at present are not a mature technology. (PFM – never mind!)

SLAC-PUB-12143 October 2006

Proposed few-optical cycle laser–driven particle accelerator structure

T. Plettner, P. Lu and R.L. Byer

E.L. Ginzton Laboratories, Stanford University,
Stanford, CA 94305
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 1.8 laser photons

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

• Potential use for electron accelerators would enable Si dielectric structures, among other possibilities
Backup
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.
Atmospheric transmission over 5-km path shows 90% transmission in 2.035-2.04 μm region.

CO\textsubscript{2} and H\textsubscript{2}O

CO\textsubscript{2}

HITRAN-PC calculation, standard atmosphere
### 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>17-23μm</td>
<td>17-23μm</td>
<td>17-23μm</td>
</tr>
<tr>
<td>Clad diameter</td>
<td>385-415μm</td>
<td>385-415μm</td>
<td>385-415μm</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>
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<tr>
<td>V value at 2μm</td>
<td>&gt;6</td>
<td>&gt;6</td>
<td>&lt;4</td>
</tr>
<tr>
<td># of modes (2μm)</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>2.7wt%</td>
<td>3.5wt%</td>
<td>3.5wt%</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)