Tm- and Ho-based femtosecond lasers for 2-µm region

A.A. Lagatsky,* and W. Sibbett

School of Physics and Astronomy, University of St Andrews, St Andrews, Fife, Scotland KY16 9SS, UK

*aal2@st-andrews.ac.uk
Outline

• 2-µm ultrashort-pulse laser sources and their possible applications

• Tm/Ho laser operational schemes and the prospects of ultrashort-pulse generation

• Experimental results
  - SESAMs design and characteristics
  - Ultrashort pulse Tm,Ho co-doped KYW and NaYW lasers around 2 µm
  - In-band pumped Ho:YLF mode-locked laser
  - Broadly tunable femtosecond operation in Tm:KYW
  - Tm:Sc$_2$O$_3$: a novel medium for femtosecond pulse generation at 2.1 µm

• Conclusions
Molecular “fingerprint” region (≈2-5 μm)

Absorption line strength, $10^{-20}$ cm$^2$/molecule·cm,

<table>
<thead>
<tr>
<th></th>
<th>Vis.-Near-IR</th>
<th>Mid-IR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>0.7-2 μm</td>
<td>2-5 μm</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>0.3</td>
<td>3000</td>
</tr>
<tr>
<td>CO</td>
<td>0.02</td>
<td>300</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>C$_2$H$_2$</td>
<td>10</td>
<td>200</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>NO</td>
<td>0.04</td>
<td>0.3</td>
</tr>
</tbody>
</table>
2-μm femtosecond sources and their possible applications

- High detection sensitivity
- Broad detection range
- High-resolution
- Short acquisition time

- Mid-IR Fourier transform spectroscopy
- Real-time monitoring of atmospheric pollution; remote chemical sensing; industrial control.
- Detection of medically important molecules, toxic gases, drugs and explosives
- Calibration of astrophysical spectrographs
2-µm femtosecond sources and their possible applications

- 3-D microstructuring of semiconductor materials

Highly-localized surgery with a femtosecond 2-µm laser?
- Femtosecond pulse regime → Reduction in the shock wave range and cavitation bubble size
Ultrafast lasers around 2μm

Average output power (mW) vs. Pulse duration (fs)

- Tm-fiber CPA
- Er-fiber/Raman/Tm-fiber
- Tm-fiber (SESAM)
- Tm:YLF (CNT)
- Tm:Lu$_2$O$_3$ (CNT)
- Tm:GdLiF$_4$ (SESAM)
- Tm:KLuW (CNT)
- Tm:Ho:YAG (SESAM)
- Tm:Ho-fiber (SESAM)
- Tm:KLuW (CNT)
- Tm:YLF (CNT)
- Tm:GdLiF$_4$ (SESAM)
- Tm:Lu$_2$O$_3$ (CNT)

Favorable directions: >1nJ, >1kW

GaSb-SDL (SESAM)
Tm fiber laser with carbon nanotube absorber

- Saturable absorber assisted mode-locking.
  - All-fiber system
  - Stable operation
  - Risk of absorber damage at high energies


92pJ, 1.32ps, 3.4mW
Tm$^{3+}$-fiber laser and Tm-CPA systems


Chirped-pulse Tm-fiber Amplifier

- NPE: nonlinear polarisation evolution mode-locking.
  - Complicated design which requires a combination of fiber and bulk optics
  - Less environmentally stable
**Tm$^{3+}$ and Ho$^{3+}$ laser operational schemes**

- **Tm-laser**
  - AlGaAs LD $\sim 800$nm
  - $\sim 1.9-2$ µm

- **Tm and Ho codoped laser**
  - AlGaAs LD $\sim 800$nm
  - $\sim 2-2.1$ µm
  - or
  - InGaAsSb/P $\sim 1.9-2$ µm
  - $\sim 2-2.1$ µm
  - *In-band* pumped Ho laser

- **Intra-cavity** pumped Ho laser
  - AlGaAs LD $\sim 800$nm
  - $\sim 2-2.1$ µm
  - Tm
  - Ho
Tm$^{3+}$ and Ho$^{3+}$ energy schemes

- Up-conversion losses in the Tm or Tm-Ho systems could prevent high-power operation.
Tm$^{3+}$ vs Ho$^{3+}$ for ultrafast lasers

- Ho$^{3+}$ ($4f^{10}$ electronic configuration) features optical absorption and emission bands with the usual sharpness of most trivalent lanthanides (i.e., those with $4f^N$ $N<11$ electronic configurations).

- Tm$^{3+}$: $4f^{12}$ electronic configuration - inhomogeneous broadening of electronic transitions.

**FWHM $\sim 170$ nm**

**FWHM $\sim 15$ nm**
Water vapor absorption could prevent continuous tunability and broadband modelocking in a Tm/Tm,Ho laser system

OH\(^-\) containing liquids are prone to bleaching effects on nanosecond time scale initiating Q-switching instabilities in a solid-state laser system
Tm-Ho codoped KYW laser

Gain spectra

Tm(5at%), Ho(0.5at%):KYW, EllNm, L=1.5mm

Tm, Ho:KYW tunability

SESAM structures design

Absorber structure

<table>
<thead>
<tr>
<th>Thickness (nm)</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>10nm</td>
<td>GaSb protective cap</td>
</tr>
<tr>
<td>41nm</td>
<td>$\text{Al}<em>{0.24}\text{Ga}</em>{0.76}\text{As}<em>{0.021}\text{Sb}</em>{0.979}$</td>
</tr>
<tr>
<td>5.5nm</td>
<td>$\text{In}<em>{0.4}\text{Ga}</em>{0.6}\text{As}<em>{0.14}\text{Sb}</em>{0.86}$ QW</td>
</tr>
<tr>
<td>20nm</td>
<td>$\text{Al}<em>{0.24}\text{Ga}</em>{0.76}\text{As}<em>{0.021}\text{Sb}</em>{0.979}$</td>
</tr>
<tr>
<td>5.5nm</td>
<td>$\text{In}<em>{0.4}\text{Ga}</em>{0.6}\text{As}<em>{0.14}\text{Sb}</em>{0.86}$ QW</td>
</tr>
<tr>
<td>50.85nm</td>
<td>$\text{Al}<em>{0.24}\text{Ga}</em>{0.76}\text{As}<em>{0.021}\text{Sb}</em>{0.979}$</td>
</tr>
<tr>
<td>0.61nm</td>
<td>GaSb protective layer</td>
</tr>
</tbody>
</table>

$A_0=0.5-2\% @ 2000-2100 \text{ nm}$

$\lambda_{\text{QW PL peak}} = 2100 \text{ nm}$
Experimental set-ups: (Tm,Ho:KYW, NaYW and Tm:KYW)

\[ w_{\text{pump}} \approx w_{\text{cavity}} = 28 \, \mu\text{m}; \quad w_{\text{SESAM}} = 80-140 \, \mu\text{m} \]

M1 and M2: HT@800nm & HR@1800-2100nm, r=-100mm

FS: IR-grade fused silica prisms

Single prism insertion: GVD \sim -114 \, \text{fs}^2

Tip-to-tip prisms separation: \sim 8 \, \text{cm} (double pass GVD \sim -1200 \, \text{fs}^2)
Stable ultrashort-pulse operation was observed when the fluence on the SESAM exceeded 42.7 $\mu$J/cm². Pulses as short as 570 fs were generated at average output power of 130 mW and pulse repetition frequency of 118 MHz, this corresponded to 1.1 nJ of the pulse energy and 1.9 kW of the peak power.

Tetragonal double tungstates

**Ho$^{3+}$ drawback**

Ho$^{3+}$ (4f$^{10}$ electronic configuration) features optical absorption and emission bands with the usual sharpness of most trivalent lanthanides (i.e., those with 4f$^N$ N$<$11 electronic configurations)

$\Delta \lambda \sim 10$-15 nm for KYW

**Partial solution: locally disordered crystals**

$\text{MT}(\text{XO}_4)_2 : (M= \text{Li}^+, \text{Na}^+); (T= \text{La}^{3+}, \text{Gd}^{3+}, \text{Lu}^{3+} \text{or Y}^{3+}); (X=\text{Mo}^{6+} \text{or W}^{6+})$

$\text{NaY(WO}_4)_2$: Czochralski growth method

Yb$^{3+}$ - $\sim 50$ fs pulses [A. García-Cortés, et al. IEEE J. Quant. Electron. 34, 758 (2007)]

Tm$^{3+}$ - 1850-2070 nm tunability [M. Rico, et al. in Advanced Solid-State Photonics, 2009, WB27]
CW Tm, Ho codoped NaYW lasers

Tm(5 at%), Ho(0.25 at%): NaYW
L = 3.8 mm, $\sigma$ - polarisation

Tm(5 at%), Ho(0.25 at%): NaYW
L = 3.8 mm, $\pi$ - polarisation

Output power, mW vs. Wavelength, nm
FWHM = 142 nm (Pabs = 1 W)

Output power, mW vs. Wavelength, nm
FWHM = 130 nm (Pabs = 0.95 W)
Modelocked Tm,Ho:NaYW ($\pi$-pol.)

PRF=144 MHz

$E_p=1.08 \text{ nJ}, P=4.2 \text{ kW}$

$F_{\text{SESAM}}=80-190 \text{ $\mu$J/cm}^2$

Modelocked Tm,Ho:NaYW ($\pi$-pol.)

\[ \tau_p = 1.7627 \frac{2|D|}{\delta \cdot E_p} \]

\[ \delta = \frac{2\pi}{\lambda} n_2 \frac{L_g}{A_{\text{eff}}} \]

\[ \frac{d\tau_p}{d|D|} = 1.7627 \frac{2}{\delta \cdot E_p} \]

\[ n_2 = 16.4 \times 10^{-16} \text{ cm}^2/\text{W @ 2060 nm} \]

\[ n_2 = 30 \times 10^{-16} \text{ cm}^2/\text{W @ 820 nm} \]  

TLD pumping of Tm,Ho codoped KYW and NaYW

Farfield position  Beamwaist position

$P_{\text{out}} = 2 \text{ W @ 802 nm}$

$M^2 \sim 5$, $P_{\text{CL}} = 80\%$

Eagleyard Photonics GmbH

Tm,Ho:KYW, $P_{\text{out}} = 200\text{ mW}$

$\tau = 675 \text{ fs}$

$\Delta \nu \Delta \tau = 0.32$

$\Delta \lambda = 6.7 \text{ nm}$

Tm,Ho:NaYW, $P_{\text{out}} = 120\text{ mW}$

$\tau = 355 \text{ fs}$

$\Delta \nu \Delta \tau = 0.32$

$\Delta \lambda = 12.6 \text{ nm}$
In-band pumped Ho:YLF ultrafast laser

In-band pumped Ho:YLF ultrafast laser

\[ P_{\text{out}} = 1.7 \text{W (4\% OC)}, \quad \text{PRF}=122 \text{ MHz}, \quad E_p=13.9 \text{ nJ} \]
Efficient and broadly tunable Tm:KYW laser

Tm(5at%):KYW, L=2mm
$E_{\text{pump}} \parallel N_m$, $k_{\text{pump}} \parallel N_g$

$\eta=73\%$ (82% theoretical limit) @ 1940 nm
$\eta=48\%$ @ 2060 nm

$\eta=73\%$ ($82\%$ theoretical limit) @ 1940 nm
$\eta=48\%$ @ 2060 nm

Efficient and broadly tunable Tm:KYW laser
Tunable Mode-locking of Tm:KYW

$w_{\text{pump}} \approx w_{\text{cavity}} = 28 \ \mu m; \ w_{\text{SESAM}} = 142 \ \mu m$

M1 and M2: HT@800nm & HR@1800-2100nm, $r=-100mm$; OC – 1% output coupler

FS: IR-grade fused silica prisms (GVD=-114fs²/mm)

Single prism insertion ~ 6 mm (double pass GVD ~ -1370 fs²)

Tip-to-tip prisms separation: 9 cm (double pass GVD~ -1800 fs²)
Broadly tunable ML with a single prism

Tunability: 1985nm (549fs, 410 mW) – 2074nm (1.32ps, 210mW)

Pulse energy: 3.9 nJ

Peak power: 7.1 kW

Optimised pulse duration

- $\tau_p = 386$ fs, Average power: 235 mW; Pulse energy: 2.4 nJ (peak power 6.2 kW)

- Modelocking thresholds: 252 $\mu$J/cm$^2$ and 227 $\mu$J/cm$^2$ on the SESAMs #1 and #2
Mode-locking stability in Tm:KYW
Tm-doped sesquioxides (Sc$_2$O$_3$, Lu$_2$O$_3$, Y$_2$O$_3$)


\[ k = 16.5 \text{ W/m} \cdot \text{K} \text{ (11 W/m} \cdot \text{K for YAG)} \]

- **Tm:Sc$_2$O$_3$ cw laser**
  \[ P_{\text{out}} = 26\text{W} \text{ (70W pump @ 796nm)} \]
Tm:Sc$_2$O$_3$ femtosecond laser

Experimental set-up

Dual wavelength operation

Intensity, a.u. vs. Wavelength, nm

Transmission, % vs. Wavelength, nm
- $\tau_p = 218$ fs, Average power: 325 mW; Pulse energy: 2.6 nJ (PRF=123 MHz)

- Modelocking threshold: 32.4 $\mu$J/cm$^2$ of intracavity fluence on the SESAM
# Ho and Tm crystalline femtosecond lasers

<table>
<thead>
<tr>
<th>Laser</th>
<th>$P_{av}^{max}$, mW</th>
<th>$\tau_{pulse}^{min}$, fs</th>
<th>$E_{pulse}$, nJ</th>
<th>$\lambda_c$, nm</th>
<th>Tunability, nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tm,Ho:KYW</td>
<td>130</td>
<td>570</td>
<td>1.1</td>
<td>2055</td>
<td>-</td>
</tr>
<tr>
<td>Tm,Ho:NaYW</td>
<td>155</td>
<td>191</td>
<td>1.08</td>
<td>2058</td>
<td>2016-2066</td>
</tr>
<tr>
<td>Ho:YLF</td>
<td>1700</td>
<td>1100</td>
<td>13.9</td>
<td>2064</td>
<td>-</td>
</tr>
<tr>
<td>Tm:KYW</td>
<td>410</td>
<td>386</td>
<td>3.9</td>
<td>2029</td>
<td>1985-2074</td>
</tr>
<tr>
<td>Tm:Sc$_2$O$_3$</td>
<td>325</td>
<td>218</td>
<td>2.6</td>
<td>2107</td>
<td>-</td>
</tr>
</tbody>
</table>
Ho and Tm crystalline femtosecond lasers

The graph shows the relationship between output power (in milliwatts) and pulse duration (in femtoseconds) for various Ho and Tm crystalline lasers. The lasers include:

- Tm-fiber CPA
- Ho:YLF
- Tm,Ho:KYW
- Tm:KYW
- Tm,Ho:NaYW
- Tm:Sc$_2$O$_3$
- Tm,Ho:KYW

The graph illustrates the performance of these lasers, with the output power increasing as the pulse duration decreases.
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  *Institute of Laser Physics, University of Hamburg, Hamburg, Germany*