Review of MPS Solid State Laser Systems

P.F. Moulton
Q-Peak
135 South Road
Bedford, MA  01730

LEOS 2006
Montreal, Canada
November 2, 2006
Outline

- General design
- Specific systems
  - Nd:YLF, 1047 and 1053 nm
  - Nd:YVO$_4$, 1064 and 1342 nm
  - Tm:YLF, 1960 nm (tunable)
  - Er:YLF, 2810 nm (tunable)
  - Yb:S-FAP, 1047 nm
  - Cr:LiSAF, 850 nm (tunable)
- Future prospects

Credits to:
Alex Dergachev, Kevin Wall, Yelena Isyanova,
Bhabana Pati, Evgueni Slobodtchikov and LLNL
For presentation – e-mail moulton@qpeak.com
Schematic of MPS design

Cylindrical Lens
Laser Crystal
Gain Sheet
Laser Mode
Multi-Passing Mirror
HR Coating for Pump

US Patent 5,774,489
# Properties of materials used in MPS systems

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Laser wavelength (nm)</th>
<th>Pump wavelength (nm)</th>
<th>Gain cross section (cm²)</th>
<th>Upper-state lifetime (μsec)</th>
<th>$\sigma\tau$ (cm²·sec) x 10²³</th>
<th>Esat (J/cm²)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd:YLF</td>
<td>1047, 1053</td>
<td>804</td>
<td>1.8 x 10⁻¹⁹, 1.2 x 10⁻¹⁹</td>
<td>480</td>
<td>8.64, 5.76</td>
<td>1.05, 1.57</td>
<td>10</td>
</tr>
<tr>
<td>Nd:YVO₄</td>
<td>1064, 1319</td>
<td>808</td>
<td>1.56 x 10⁻¹⁸, 6 x 10⁻¹⁹</td>
<td>100</td>
<td>15.6, 6.0</td>
<td>0.12, 0.25</td>
<td>11</td>
</tr>
<tr>
<td>Tm:YLF</td>
<td>1950</td>
<td>792</td>
<td>1 x 10⁻²¹</td>
<td>15600</td>
<td>1.56</td>
<td>99.0</td>
<td>12</td>
</tr>
<tr>
<td>Er:YLF</td>
<td>2810</td>
<td>968</td>
<td>3 x 10⁻²⁰</td>
<td>2800</td>
<td>12.0</td>
<td>2.35</td>
<td>13</td>
</tr>
<tr>
<td>Yb:S-FAP</td>
<td>1047</td>
<td>900</td>
<td>7.3 x 10⁻²⁰</td>
<td>1260</td>
<td>9.20</td>
<td>2.59</td>
<td>14</td>
</tr>
<tr>
<td>Cr:LiSAF</td>
<td>850</td>
<td>680</td>
<td>4.8 x 10⁻²⁰</td>
<td>70</td>
<td>0.33</td>
<td>4.85</td>
<td>15</td>
</tr>
</tbody>
</table>


Nd:YLF
MPS oscillator I/O data at 1047 and 1053 nm

![Graph showing the relationship between pump power and output power for 1047 nm and 1053 nm wavelengths. The graph includes a line with a 52% slope, indicating a linear relationship between pump power and output power.]
Q-switched properties at 1047 nm

6.6 mJ, 7.7 ns pulses at 3 kHz
40-W bar-pumped, 1047-nm, MPS MOPA

Oscillator

Gain Modules

Amplifier

54 W cw, >50 W Q-switched (5-50 kHz) with 128 W total pump $M^2 \approx 1.15$

26.5 W
MPS with short-pulse MOPA

Short-pulse, AO Q-switched Nd:YLF laser

30-100 kHz, 8-20 nsec
85 W average power at 1047 nm

With harmonic generation at 30 kHz:
45 W at 523.5 nm
25 W at 349 nm
10 W at 262 nm

1 W at 30-100 kHz
Schematic of MPS regenerative amplifier

M1-10, HR 1047 nm mirrors; TFP, thin film polarizers; GM, gain module; λ/4, quarterwaveplate; λ/2, halfwaveplate; Lens 1-2, cylindrical lenses; FR, Faraday rotator; FI, Faraday isolator; PC, Pockels cell

100-ps, 2.5 nJ at 5 kHz in, 5 mJ out
25 W average power at 1047 nm
Nd:YVO$_4$
Schematic and layout of MPS with Nd:YVO$_4$
Performance of MPS Nd:YVO$_4$ cw oscillators

- Multimode 1064 nm: 51.6% slope
- TEM00 1064 nm: 46.3% slope
- Multimode 1342 nm: 36.1% slope
- TEM00 1342 nm: 26.3% slope
1064-nm Q-switched Nd:YVO₄ oscillators

![Graph showing the relationship between pulse rate (kHz) and average power (W) for E-O and A-O Q-Switches.](image-url)
Prior examples of MPV amplifier systems

1064 nm:
- 50 W average
- 50 kHz rate
- 10 ns PW

1342 nm
- 27 W average
- 50 kHz rate
- 25 ns PW

700 mW CW at 1064-nm
Single-frequency

7 W CW
Amplified microchip lasers

Design: Nd:YVO4-amplified microchip laser
Pulse duration: 200-300 ps
Pulse energy: 200 uJ at 532 nm
Pulse rate: 2 kHz

Photograph of hardware designed for remote, autonomous operation

New results: 14 W average power, 250-ps pulses at 1064 nm, 10-kHz rate
Ps high-repetition-rate Nd:YVO$_4$ MOPA

- Amp 1: ~28 W
- Amp 2: ~42 W
- Amp 3: ~56 W
- Pre-amp: 7 W
- SESAM ML OSC: 75-750 MHz, 30 ps

> 60% SHG conversion at 75 MHz, 34 W average power at 532 nm
Tm:YLF
Pi-polarized absorption, emission in Tm:YLF
I/O curves for oscillator, 3.5 % Tm:YLF

- 37% slope efficiency, Multimode
- 28% slope efficiency, TEM00
Tuning covers 1910-2070 nm

Output power (W)

Wavelength (nm)

- T=13%
- T=3%
Calculated Tm:YLF gain spectrum
Er:YLF
- high Er concentration
- 980-nm pump
- strong up-conversion
- high heat generation
Er:YLF cw I/O curves at 2810 nm

- 16.5% slope efficiency
- 15% slope efficiency
### Line tuning of cw Er:YLF laser

![Graph showing line tuning of cw Er:YLF laser](image)

<table>
<thead>
<tr>
<th>Manifold</th>
<th>4I/11/2</th>
<th>4I13/2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Energy, cm⁻¹</td>
<td>10222</td>
<td>10235</td>
</tr>
<tr>
<td>Wavelength (nm)</td>
<td>nm</td>
<td>nm</td>
</tr>
<tr>
<td>4I13/2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>6738</td>
<td>2870.3</td>
</tr>
<tr>
<td>6</td>
<td>6724</td>
<td>2858.8</td>
</tr>
<tr>
<td>5</td>
<td>6697</td>
<td>2836.9</td>
</tr>
<tr>
<td>4</td>
<td>6674</td>
<td>2818.5</td>
</tr>
<tr>
<td>3</td>
<td>6579</td>
<td>2745.0</td>
</tr>
<tr>
<td>2</td>
<td>6539</td>
<td>2715.2</td>
</tr>
<tr>
<td>1</td>
<td>6535</td>
<td>2712.2</td>
</tr>
</tbody>
</table>
Yb:S-FAP
Yb:S-FAP absorption with 900-nm pump line and 1047-nm laser line

CW and QCW operation of Yb:S-FAP

![Graph showing CW and QCW operation with different duty cycles and slope efficiencies.]

- 33% duty: 15% slope efficiency
- 40% duty: 16% slope efficiency
- 50% duty: 21% slope efficiency
- CW: 15% slope efficiency

Total peak diode power (W) vs. Peak output power (W)
Amplification of 20-ns pulses from Nd:YLF

- Input Pulse Energy (mJ)
- Output Energy (mJ)

- experiment
- theory
Cr:LiSAF
Diode-pumped Cr:LiSAF laser generates 3 W of cw power at 850 nm

Cr:LiSAF has the bandwidth to support 10 fs pulses
Future:
Higher-power bars
Cryogenic cooling
MPS Nd:YLF data with 90-W bars

- 64% slope efficiency
- 31% overall efficiency
- $M_x^2 = 1.05$
- $M_y^2 = 1.35$
Single-frequency, 65 mJ, 1 kHz Nd:YLF MOPA

30-W Fiber-coupled diode

Single-frequency, passively Q-switched Nd:YLF Oscillator, 1 mJ

Double Isolator

Pre-amplifier 1
5 mJ

W/2x60 W diodes

Pre-amplifier 2
15 mJ

W/2x60 W diodes

Pre-amplifier 3
24 mJ

W/2x100 W diodes

50% Beamsplitter

Channel I
Final amplifier
W / 285 W nLight Cascade Diode

Channel I Output, 35 mJ

Channel II
Final amplifier
W / 285 W nLight Cascade Diode

Channel II Output, 30 mJ
Cryo-cooled Yb:YAG has greatly enhanced potential high-power performance

- $\text{FOM}_b$ and $\text{FOM}_d > 30X$ larger in 100 K Yb:YAG compared with 300 K Nd:YAG
  - ~ >12X larger than 300 K Yb:YAG (assuming equal optical efficiencies)
- Broad absorption band maintained at low temperature
  - Sharpening of absorption features at low temperature does not drive pump wavelength control requirements

Courtesy: T.Y. Fan, MIT/LL
Crystal mount achieves effective cooling
Single and five-Pass Results

Maximum output power obtained was 330 W. The optical to optical efficiency was 46 % and the slope efficiency was 49 %.
The MPS design has been applied to a variety of laser materials, and has been used to generate record performance from a number of systems.

**Improvements needed:**
- Nd:YVO$_4$ – larger crystals
- Tm:YLF – Tm:fibers will dominate in cw
- Er:YLF – optimization of doping, thermal management
- Yb:S-FAP – higher doping, better pump lasers

Output powers will scale up with the improved performance of diode pump lasers.

Cryogenic cooling will provide spectacular improvements in power output.

Even with fiber lasers, bulk crystals will still be the practical source for energetic pulses with high beam quality.