Recent Advances in Mid-IR Solid State Lasers, OPOs and QCLs

Peter Moulton
VP/CTO
Q-Peak, Inc.
Outline

• Diode-pumped mid-IR sources
  – Er:YLF
  – Tm-laser-pumped Ho:YLF
• OPOs
  – ZnGeP₂ (ZGP) OPO pumped by Ho:YLF laser
  – Tandem OPO (KTA – CdSe)
• QCL-based sources
Commercial products developed by Q-Peak

Laser 1-2-3

Titan CW, P, ML

MPS Lasers (early)

MPS Gain Module

MPS Laser Head
The Laser 1-2-3 provided a range of wavelengths, into the mid-IR
Pump cavity, rod and mirrors for solid state laser
Q-Peak’s DPSSL design obtains high efficiency and high beam quality with side-pumping.

Multi-Pass Slab (MPS)
US Patent 5,774,489

Applied to Nd:YLF, Nd:YVO₄, Nd:YAG
Yb:S-FAP, Yb:YAG, Tm:YLF, Er:YLF, Cr:LiSAF

“Gain Module”
Er$^{3+}$ Energy Level Diagram

Energy Levels:
- $^4F_{7/2}$
- $^2H_{11/2}$
- $^4S_{3/2}$
- $^4F_{9/2}$
- $^4I_{9/2}$
- $^4I_{11/2}$
- $^4I_{13/2}$
- $^4I_{15/2}$

Transitions:
- $W_{50}$
- $W_{22}$
- $W_{11}$

Pump transition at 2.8 $\mu$m

States:
- $N_1$
- $N_2$
Earlier end-pumped work produced cw powers from several materials.
Previous results – Diode-pumped Er:YLF-lasers

• Maximum slope efficiency:
  – ~ 40% - Ti:Sapphire excitation (970 nm, longitudinal)
    M.Pollnau et al., “Efficiency of Erbium 3-μm crystal and fiber lasers” IEEE J. of Quantum Electronics, 32, 657-663 (1996)
  – ~ 35% - Diode-Pumped (970 nm, longitudinal)

• Maximum CW output:
  – ~ 1.1 W Diode-pumped (970 nm, longitudinal, fiber-coupled diode laser)
    T. Jensen et al. (see above)

• Drawbacks:
  • difficult to scale to higher powers
  • fracture of the laser elements at 4-6 W pump power (0.3-0.5 mm spot)
Absorption Properties of Er:YLF Laser Crystals

Polarized absorption spectra for 15% Er:YLF crystal at 300 K.
Brewster-angle design for side-pumped Er:YLF laser
Er:YLF Active Element:
Brewster/Brewster-cut slab:
28-mm long
Clear aperture 1.25 x 6 mm.

a) Compact 3-pass resonator

b) “Long” resonator
Rate equations:
\[
dN_2/dt = W + W_{11}(N_1)^2 - W_{22}(N_2)^2 - N_2/\tau_2,
\]
\[
dN_1/dt = \beta_{21} N_2/\tau_2 + W_{22}(N_2)^2 - 2W_{11}(N_1)^2 - N_1/\tau_1,
\]

The net gain coefficient:
\[
g = \sigma_{21} (b_2 N_2 - b_1 N_1),
\]

Definitions:
- $W_{11}$, $W_{22}$ - up-conversion rate parameters,
- $\tau_1$ and $\tau_2$ - lifetimes for spontaneous decay and
decay,
- $\beta_{21}$ - the branching ratio.
- $\sigma_{21}$ - spectroscopic cross section for the transition and
- $b_1$, $b_2$ - Boltzmann factors for the lower and upper manifolds.

Theoretical Model

**Table. Values for 15% Er:YLF used in the calculations** (Based on the data from: M.Pollnau et al. IEEE J. QE, 321, 657-663 (1996)).

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_1$</td>
<td>10 msec</td>
</tr>
<tr>
<td>$\tau_2$</td>
<td>4.0 msec</td>
</tr>
<tr>
<td>$W_{11}$</td>
<td>$3 \times 10^{-17}$ cm$^3$/sec</td>
</tr>
<tr>
<td>$W_{22}$</td>
<td>$1.8 \times 10^{-17}$ cm$^3$/sec</td>
</tr>
<tr>
<td>$\beta_{21}$</td>
<td>0.39</td>
</tr>
<tr>
<td>$\sigma_{21}$</td>
<td>$3 \times 10^{-20}$ cm$^2$</td>
</tr>
<tr>
<td>$b_1$</td>
<td>0.113</td>
</tr>
<tr>
<td>$b_2$</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Gain Calculation

- Pump Rate, cm$^3$
- Gain coefficient, cm$^{-1}$

Linear, Square root, Calculation

Experiment points for 10-W and 20-W pump conditions.
Er:YLF CW Laser Operation
Three-Pass Geometry

<table>
<thead>
<tr>
<th></th>
<th>short</th>
<th>long</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR mirror</td>
<td>2600-3000 nm</td>
<td>2600-2900 nm</td>
</tr>
<tr>
<td>Output coupling</td>
<td>T ~ 4% at ~ 2600-2900 nm</td>
<td>T ~ 4% at 2600-2900 nm</td>
</tr>
<tr>
<td>Resonator length</td>
<td>~ 20 cm</td>
<td>~ 40 cm</td>
</tr>
</tbody>
</table>

16.5% slope efficiency
15% slope efficiency
Er:YLF quasi-CW Laser Operation
Three-Pass Geometry

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR mirror</td>
<td>2600-3000 nm</td>
</tr>
<tr>
<td>Output coupling</td>
<td>T ~ 4% at 2600-2900 nm</td>
</tr>
<tr>
<td>Resonator length</td>
<td>~ 40 cm</td>
</tr>
</tbody>
</table>
Calculated Wavelengths for Transitions Between $^4I_{11/2}$ and $^4I_{13/2}$ Manifolds in Er:YLF

<table>
<thead>
<tr>
<th>Manifold</th>
<th>Level</th>
<th>$^4I_{11/2}$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Energy, cm$^{-1}$</td>
<td>10222</td>
<td>10235</td>
<td>10283</td>
<td>10289</td>
<td>10315</td>
</tr>
<tr>
<td></td>
<td></td>
<td>nm</td>
<td>nm</td>
<td>nm</td>
<td>nm</td>
<td>nm</td>
<td>nm</td>
</tr>
<tr>
<td>$^4I_{13/2}$</td>
<td>7</td>
<td>6738</td>
<td>2870.3</td>
<td>2859.6</td>
<td>2820.9</td>
<td>2816.1</td>
<td>2795.6</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>6724</td>
<td>2858.8</td>
<td><strong>2848.2</strong></td>
<td><strong>2809.8</strong></td>
<td>2805.0</td>
<td>2784.7</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6697</td>
<td><strong>2836.9</strong></td>
<td>2826.5</td>
<td>2788.6</td>
<td>2784.0</td>
<td>2764.0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>6674</td>
<td>2818.5</td>
<td><strong>2808.2</strong></td>
<td><strong>2770.9</strong></td>
<td>2766.3</td>
<td>2746.5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6579</td>
<td>2745.0</td>
<td>2735.2</td>
<td>2699.8</td>
<td>2695.4</td>
<td>2676.7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6539</td>
<td><strong>2715.2</strong></td>
<td>2705.6</td>
<td>2670.9</td>
<td>2666.7</td>
<td>2648.3</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>6535</td>
<td>2712.2</td>
<td>2702.7</td>
<td>2668.1</td>
<td><strong>2663.8</strong></td>
<td>2645.5</td>
</tr>
</tbody>
</table>

**Note:** Bold numbers indicate wavelengths for which lasing has been obtained in prior work.
Wavelength tuning of Er:YLF laser with a 1-plate birefringent filter
Mid-IR source: Tm-doped laser-pumped, Ho:YLF laser pumped, ZGP OPO

- Tm laser
- Ho:YLF laser
- ZGP OPO

CW 1940 nm
Q-switched 2050 nm
100 mJ
Broadly tunable mid-IR
Why a laser pumping a laser pumping a laser?

• Semiconductor diode laser
  – high electrical-optical efficiency *but*
  – only cw-like output, poor beam quality at high powers

• Tm solid state laser (bulk or fiber)
  – good (in theory) conversion of poor quality beam from diode lasers into diffraction-limited beam *but*
  – limitations in stored energy and nonlinear/damage issues prevent generation of high pulse energies

• Bulk solid state Ho:YLF laser
  – good conversion of pump power to output power
  – high energy storage and extraction capability allows generation of high-peak-power pulses
References on resonantly pumped Ho lasers


• $1 \rightarrow 2$ pump process due to cross-relaxation
• low up-conversion
• low heat generation (~20 %)

\[ \text{Pump \sim 790 \text{ nm}} \]

\[ \text{Lasing \sim 1.9 \text{ \mu m}} \]
Polarized emission cross-section $^3F_4 \rightarrow ^3H_6$ for Tm:YLF (calculated from absorption spectra).
Gain Calculation – 3.5% Tm:YLF

Polarized gain in Tm:YLF at two values of inversion fraction

\[
g(\lambda) = N \left[ p \cdot \sigma_{em}(\lambda) - (1-p) \cdot \sigma_{abs}(\lambda) \right],
\]

where \( p \) – inversion fraction, \( N \) - Tm-concentration
Tunable power from Tm:YLF laser
**Tm:YLF Active Element:**

Rectangular slab:
- 22-mm long
- Clear aperture 2x6 mm.
Tm:YLF – Dual GM Oscillator – 3 passes

25% slope efficiency

Output power, W

Diode pump power, W
Ho:YLF vs. Ho:YAG

Why Ho:YLF (Q-Peak, NASA)?
- Long upper laser level lifetime ~ 15 ms (in theory)
- Highest emission cross-section known for Ho-doped crystals
  \[ \sigma = 1.84 \times 10^{-20} \text{ cm}^2 \]
- \( E_{\text{sat}} = 5.3 \text{ J/cm}^2 \)
- Naturally birefringent material
- Low \( dn/dT \) \( \rightarrow \) weak thermal lensing
- \~5% quantum defect

Compared to Ho:YAG (BAE, SORC)
- Upper state lifetime 7 ms
- Emission cross section \( 0.98 \times 10^{-20} \text{ cm}^2 \)
- \( E_{\text{sat}} = 9.6 \text{ J/cm}^2 \)
- 10% quantum defect
- Isotropic, higher thermal lensing, stress birefringence
- Superior thermo-mechanical properties
Pumping Ho:YLF with Tm:YLF laser

Absorption coefficient, cm$^{-1}$

Wavelength, nm

Red line: Ho abs - Pi
Blue line: Tm-tuning

2.0% Ho:YLF
Ho:YLF gain is predicted to be high for a 59% inversion fraction.
DM – Dichroic Mirror,
AOM – Acousto-Optic Modulator,
OC – Output Coupler,
HR – High Reflector
CW Ho:YLF Laser Operation (TEM$_{oo}$)

- Total Tm pump power, W
- Ho:YLF CW output, W

- 54% slope efficiency
- 45% slope efficiency

Symbols:
- Diamond (10%)
- Square (15%)
- Circle (40%)
- Dot (70%)
Ho:YLF laser operation is in $\text{TEM}_{\infty}$ mode
Ho:YLF – Q-Switched Operation (TEM_{00})

![Graph showing the relationship between repetition rate, Hz, and output power, W, versus pulse energy, mJ. The graph includes data points and a trend line.](https://via.placeholder.com/150)
Ho:YLF – Pulsewidth vs repetition rate
Ho-laser Power Scaling

- CW Tm:fiber lasers with output >100 W emerge as alternative to bulk Tm-laser:
  - Turn key operation
  - Cost-effective
  - Maintenance-free
  - Fiber delivery (no surprise!)

Tm-fiber laser TLR-100-1940
(IPG Photonics, www.ipgphotonics.com)

<table>
<thead>
<tr>
<th>Operation regime</th>
<th>CW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational temperature</td>
<td>RT</td>
</tr>
<tr>
<td>Output power</td>
<td>≥ 100 W</td>
</tr>
<tr>
<td>Lasing wavelength range</td>
<td>1750-2200 nm</td>
</tr>
<tr>
<td>Polarization:</td>
<td>Random</td>
</tr>
<tr>
<td>Linewidth</td>
<td>≤ 2 nm</td>
</tr>
</tbody>
</table>
Schematic layout of the fiber-pumped Ho:YLF laser shows two-crystal design.

DM – Dichroic Mirror,
AOM – Acousto-Optic Modulator,
OC – Output Coupler,
HR – High Reflector
CW laser operation provides 40-W of output power.

**Graph:**
- **Output transmission**
- **Ho:YLF output, W**
- **Total Tm-pump power, W**
- **Slope Efficiency 42%**
- **Quantum efficiency 74% (absorbed)**

- **40%** (closed circles)
- **70%** (open circles)
Ho:YLF Q-switched laser operation observed at pulse rates from 200-1000 Hz

![Graph showing Ho:YLF pulse energy vs. Total Tm-pump power with different focusing settings: "Loose" focusing and "Moderate" focusing. The graph includes data points for w1-1k, w1-400, w1-200, w2-200, and w2-400. The text "We chicken out" is also present.]
Ho:YLF effective storage time is around 2 msec based on energy vs. pulse rate data.

Reasons: Bleaching, upconversion?
OPOs
Theoretical tuning curve for Ho:YLF-pumped ZGP OPO
ZGP OPO - Layout

- ZGP OPO:
  - ZGP 1 cm-long
  - Type I, 53°-cut
  - Flat/flat resonator
  - Singly resonant cavity
  - Pump – double pass
  - ~6 cm-long resonator
  - OC 38% at 3.2 um

HR 3.2 um
HT 2.05 and 5.7 um

R=38% 3.2 um
HR 2.05 um
HT 5.7 um
ZGP OPO operation – pulse energy at 3200 nm

Slope efficiency:
- 50 Hz: 60%
- 200 Hz: 56%
- 400 Hz: 63%
Packaged Tm:YLF, Ho:YLF, ZGP OPO system
Conclusions

- Fiber-laser pumped Ho:YLF crystal (and similar materials) combines best features of fiber and bulk solid state lasers
  - High beam quality and efficiency of fiber lasers
  - Energy storage capability of bulk lasers
- Recent advances in commercial (IPG) Tm:fiber lasers have made 100-W devices available. Future powers even higher?
- Ho:YLF laser has a favorable combination of energy storage and high gain cross section, suitable for high-energy, short-pulse Q-switched oscillators and amplifiers at 2050 nm
- 2050-nm wavelength is eyesafe, transmits well through the atmosphere and is a good pump wavelength for ZGP OPOs providing coverage of entire mid-IR wavelength region
- Scaling to 40 W average power, 45 mJ pulses at 20 ns to date
- Stayed tuned, another 200 W of pump power yet to go!
Early Nd:YLF MOPA system generated
40 W Q-switched at 5 kHz

50 W CW
40 W Q-Sw @ 5 kHz
14-ns pulsewidth

Two-module Nd:YLF Oscillator

EO Q-switch

2nd Stage Amplifier

Cylinder lens

1st Stage Amplifier

Cylinder lens
Two-Gain-Module oscillator generated 14-ns pulses at a 5-kHz pulse rate

10 ns per division
Data on IR OPOs pumped by MPS system

- **Pump source**: 40 W, 5 kHz, 15 ns Nd:YLF MOPA
- **KTA OPO**
  - **60-mm crystal length, 80-degree cut**
    - 30 W pump, 5 kHz PRR
    - 10 W at 1530 nm, 3 W at 3340 nm
  - **40-mm crystal length, 60-degree cut**
    - 31 W pump, 5 kHz PRR
    - 2.5-5 W of idler tunable from 2100-3100 nm
- **PPLN OPO**
  - **19-mm crystal length, 30.8-um pitch**
    - 30 W pump, 5 kHz PRR
    - 5.2 W at 2610-nm idler, 3W at 1720-nm signal
Plot of KTP and KTA IR transmission

- KTA 2cm
- KTP 2cm

T = 75% @ 3297nm
T = 23% @ 3297nm
Tuning curve for MPS-driven KTA OPO
Design for high-power KTA OPO

Four KTA Crystals 1 x 1 x 2 cm each

- Moderate threshold
- Moderate efficiency
- High damage
- Low feedback
Highest-average-power OPO uses KTA

High-average-power, 100-Hz OPO used KTA


Results with two different pump lasers, pump laser pulsewidths 22.5 and 17.5 ns
Tandem OPO for infrared DIAL
Tandem OPO scheme

Nd-doped, Q-switched laser

KTA OPO

CdSe OPO

IR seed source

1.5 - 3.6 \( \mu \text{m} \)

3.3 - 11 \( \mu \text{m} \)

Angle-tuned

Pump-tuned, NCPM

Nd-doped seed laser

Or: PPLN, other KTP isomorphs

Or: AgGaSe\(_2\), ZnGeP\(_2\)
Tandem OPO tuning with x- and y-cut KTA

- CdSe signal and idler
- KTA signal and idler

Wavelength (um) vs. KTA Phasematch angle (degrees)
Angle-tuning data on KTA OPO

Wavelength (um)

Angle (degrees)

y-cut idler data
x-cut idler data
x-cut signal data
y-cut signal data
Seeded Nd:YLF ring pump laser (lamp pumped)
Tandem OPO demonstration

EOSI 2010 External Cavity Diode Laser 1530-1560 nm

Seed laser

40-50 mJ signal
25 mJ idler

KTA

Optical isolator

Nd:YLF pump laser

>200 mJ, 20 Hz

CdSe OPO signal

CdSe OPO idler
8.3-10.6 um
3-4.5 mJ

KTA OPO idler
3.0-3.45 um

KTA OPO idler

CdSe
KTA OPO pumping: seeded and unseeded laser

![Graph showing the relationship between pump energy and KTA OPO total output energy for seeded and unseeded pumps.](image-url)
I/O data for x- and y-cut KTA

OPO output energy (mJ) vs. Pump energy (mJ)

- ▲ y-cut NCPM signal
- ▲ y-cut NCPM idler
- ▲ x-cut 66 deg. signal
- ▲ x-cut 66 deg. idler
KTA OPO pump and signal pulse profiles

Seeded pump

Unseeded pump

1 - pump pulse
2 - signal pulse
CdSe OPO I/O data

![Graph showing the relationship between pump energy (mJ) and total OPO energy (mJ) for 3.45 um and 3.18 um pumps. The graph includes data points and trend lines for each wavelength.](image_url)
CdSe OPO pump and signal pulse profiles
Diode-pumped, 1-kHz Nd:YLF
OPO pump-system layout

OPO pump beam

QCW-end-pumped, AO Q-switched, Nd:YLF Oscillator

L1 & L4, collimating lenses, L2 & L3, relay-imaging lenses
Nd:YLF pump generates 18 mJ/pulse at 1 kHz, with 10-nsec-duration pulses, TEMoo output.

![Graph showing output pulse energy vs. total amplifier pump power.](image)

- 0.9 mJ
- 1.9 mJ
- 2.8 mJ
- 3.6 mJ
- 4.7 mJ
KTA OPO output energy (mJ)

- Total
- Signal
- Idler

$y = 0.4738x - 0.9086$
CdSe OPO performance
(signal 5 µm, idler 10.5 µm)
Overall design of rapidly tunable, 1-kHz PRR Tandem OPO

Legend:
- Laser diode current
- MPL control (current settings, burst mode)
- AOBD control (RF, burst mode)
- Rotation control (angle)
- Trigger pulse
- External burst
- Mid IR output

MPL

RF Synthesizer (rapid tuning)

Rotation control (slow tuning)

PC 1

PC 2

AMP 1

AMP 2

AMP 3

AOBD

Rotary stages

External burst

Mid IR output
QCL-based systems
PSI (parent company of Q-Peak) now adding QCLs into gas sensing systems

- Direct current injection devices from $0.43 \rightarrow 2.0 \, \mu m; \ 3.3 \rightarrow 105 \, \mu m$
- Frequency converted devices from $0.22 \rightarrow 0.43 \, \mu m$ (SHG); $2.3 \rightarrow 4.5 \, \mu m$ (DFG, OPO)
- 7.16 micron DFB from Alpes Lasers
- 4 cm\(^{-1}\) total tuning range with TE cooler
- 1 cm\(^{-1}\) high-speed current tuning range at fixed T
TE-Cooled QCL Mount

- Integral current pulser – 3 ns pulsewidth, 3 MHz rep rate
- Typical average power ~ 1 mW

- Dual-Stage TE-cooler for 270 – 320 K operation
- Singlemode over full current tuning range >19 dB SMSR

$\lambda = 3.3564\, \mu\text{m}$

M115C ; Epi-Up DFB ICL
8.5-µm x 1.013-mm mesa

- >5 mW output power
• Compared to simulated ethane absorption spectrum
• FTIR-limited laser bandwidth

- ~ 1.5 cm\(^{-1}\) current tuning range at fixed T
Quantum-cascade-laser (QCL) seeded OPO for atmospheric sensing (NASA-funded)

Design goal:
200 mJ/pulse
>50-Hz PRR
pump laser

Photograph of ring-cavity
ZGP OPO
Seed laser is 4.6-μm, cw QCL
Seed laser can be current-tuned