Single-frequency operation of a Cr:YAG laser from 1332-1554 nm

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• Properties of Cr:YAG
• Cr:YAG laser design considerations
• Broadband laser results
• Single frequency design and results
• Summary
Cr$^{4+}$:YAG energy-level diagram ($D_{2d}$)

Complications:
- Cr$^{3+}$ ions
- Charge-compensation ions
- Multiple sites

Ref: Chang et al, OSA TOPS Vol. 19, ASSL
Cr:YAG emission (not gain) spectrum

Eilers et al., IEEE JQE 29, 2508 (1993)
Water-vapor absorption is an issue

6 Torr pressure, 1-m path
Tetrahedral symmetry for Cr in YAG leads to large transition cross sections, short lifetime

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Center wavelength (nm)</th>
<th>Tuning range (nm)</th>
<th>Eff. gain cross section (10-19 cm²)</th>
<th>Lifetime (µs)</th>
<th>Max. eff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti:sapphire</td>
<td>800</td>
<td>680-1100</td>
<td>2.5-3</td>
<td>3.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Cr:LiSAF</td>
<td>850</td>
<td>780-1050</td>
<td>0.32</td>
<td>67</td>
<td>0.53</td>
</tr>
<tr>
<td>Cr:YAG</td>
<td>1430</td>
<td>1340-1570</td>
<td>3</td>
<td>4</td>
<td>0.25</td>
</tr>
<tr>
<td>Cr:ZnSe</td>
<td>2400</td>
<td>2300-2500</td>
<td>8</td>
<td>7</td>
<td>1.0</td>
</tr>
<tr>
<td>Ce:LiSAF</td>
<td>292</td>
<td>280-297</td>
<td>60</td>
<td>0.028</td>
<td>0.35-0.7</td>
</tr>
</tbody>
</table>

Note: we measured 4.5-4.6 microseconds Cr:YAG lifetime at 300 K (radiative QE is likely less than unity, since 4 K lifetime is 25-30 usec)
Cr:YAG absorption spectrum

Design considerations for cw Cr:YAG lasers

- For various reasons, the concentration of Cr$^{4+}$ centers is limited, so pump absorption is typically 1 cm$^{-1}$
  - *This limits pump focusing because of diffraction of pump beam in crystal absorbing region. Favors diffraction-limited pump laser.*

- ESA of pump, bleaching of ground state absorption and thermal quenching call for minimizing pumping levels
  - *Both output coupling and cavity losses must be minimized to permit reasonable efficiencies. Gain is limited.*
  - *Crystal temperature rise must be minimized to avoid increasing the threshold pump level*

- Despite variations in crystal environment for active ion, the broadband nature of the vibronic transition means the laser is essentially homogeneously broadened
  - *Elimination of spatial hole burning should lead to single-frequency operation, similar to Nd:YAG and Ti:sapphire*
Pump laser is diode side-pumped Nd:YLF

Gain module

Nd:YLF slab

Diode Laser bar

1047 nm

System is early prototype of Q-Peak MPS-1047 CW 10
Available TEM\textsubscript{00} pump power \approx 7 W
Standing-wave, Cr:YAG broadband tuning

Pump: 7.3 W

Output power (mW) vs. Wavelength (nm)

- T = 1.75%
- T = 1.25%
- T = 0.50%
Towards tunable, single-frequency operation

- Basic approach to single-frequency operation was to make a unidirectional, 4-mirror ring cavity, similar to Ti:sapphire ring laser.
- Because of the low gain in Cr:YAG and the need to minimize intracavity losses, the choice of an optical diode is critical. For the non-reciprocal element, we looked at:
  - YIG
  - TGG
  - Various glasses
  - Cr:YAG
- The best results were obtained by using the gain medium itself as the element. We placed a small magnet near the laser crystal, and aligned the cavity out of plane to compensate for the Faraday rotation.
Schematic of Cr:YAG single-frequency laser

- MPS-1047 CW10 DIODE-PUMPED Nd:YLF LASER
- CaF$_2$ ETALON
- Single-plate birefringent tuner
- Cr:YAG CRYSTAL (in magnetic field)
- OUTPUT
- M4
- M2
- M1
- M3
- PUMP LENS
- 1047-nm PUMP BEAM
Cr:YAG laser layout

OC, Etalon, HR, BRF, Cr:YAG, Pump
Single-frequency tuning curves

- Mirror set 1
  - T=0.5%

- Mirror set 2
  - T=0.1%

Output power (mW) vs. Wavelength (nm)
Scanning Confocal Etalon traces

Upper trace: 100x expansion 3.6 MHz linewidth (etalon limit)

Lower trace: Two peaks 2 GHz spacing (etalon FSR)
Summary

- Cr:YAG has some fundamental limits to efficiency and gain because of the ion energy-level structure and interaction with the host crystal.
- Despite these limits, Cr:YAG, when pumped by a diffraction-limited, multi-Watt laser, can provide Watt-level cw outputs in a broadly tunable wavelength region centered around 1470 nm.
- Because the laser transition is essentially homogeneously broadened, efficient, single-frequency operation is possible by elimination of spatial hole-burning.
- We obtained single-frequency, broadly tunable (1332-1554 nm) operation (0.68 W max. power) by using the laser crystal itself as the Faraday element in a unidirectional, non-planar ring cavity.