Noncollinear Optical Parametric Amplifiers for Ultra-Intense Lasers

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Optical parametric chirped-pulse amplification (OPCPA) offers the potential for intensities exceeding $10^{24}$ W/cm$^2$

- LLE is developing the technologies necessary for an ultra-intense OPCPA system pumped by OMEGA EP

- Large DKDP$^1$ crystals can provide ~200 nm of gain, centered at 910 nm
  - sufficient bandwidth to support ~15-fs pulses
  - pumped by existing kilojoule Nd:glass lasers
  - grown in large sizes, so they can scale-up energy to kilojoule level

- A midscale optical parametric amplifier line (OPAL) is under construction
  - 15 fs, 7.5 J, $10^{22}$ W/cm$^2$
  - demonstrate technologies that are scalable to a kilojoule system

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$^1$Deuterated potassium dihydrogen phosphate
Many people (internal and external) have contributed to this project

<table>
<thead>
<tr>
<th>Laser development and optical engineering:</th>
<th>Mechanical:</th>
<th>Experimental:</th>
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<tr>
<td>S.-W. Bahk</td>
<td>G. Gates</td>
<td>D. H. Froula</td>
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<td>I. A. Begishev</td>
<td>J. Magoone</td>
<td>D. Haberberger</td>
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<td>J. Bunkenburg</td>
<td>G. Martin</td>
<td>D. D. Meyerhofer</td>
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<td>C. Dorrer</td>
<td>J. Martin</td>
<td>J. F. Myatt</td>
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<td>R. K. Jungquist</td>
<td>M. J. Shoup III</td>
<td>P. M. Nilson</td>
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<td>T. J. Kessler</td>
<td>R. Taylor</td>
<td>C. Stoeckl</td>
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<td>E. Kowaluk</td>
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<td>L. McIntire</td>
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<td>C. Mileham</td>
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<td>M. Millechia</td>
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<td>S. F. B. Morse</td>
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<td>A. V. Okishev</td>
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<tr>
<th>Electrical:</th>
<th>System:</th>
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<tbody>
<tr>
<td>W. A. Bittle</td>
<td>A. Agliata</td>
</tr>
<tr>
<td>G. Kick</td>
<td>C. Rees</td>
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<td>R. G. Peck</td>
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<th>External:</th>
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<tbody>
<tr>
<td>N. Anderson (Semrock)</td>
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<td>J. Fini (OFS)</td>
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<tr>
<td>S. Hädrich (Jena)</td>
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<tr>
<td>M. Kirchner (KMLabs)</td>
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<td>E. Riedle (LMU)</td>
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<td>J. Rothhardt (Jena)</td>
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<td>C. Hall (QED)</td>
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An ultra-intense OPCPA extension to OMEGA EP would reach focused intensities approaching $10^{24}$ W/cm$^2$.

This laser would be a world-class tool for fundamental science at new intensity regimes.
Noncollinear optical parametric amplifiers (NOPA’s) amplify pulses using a nonlinear three-wave process

- Energy conservation: \( \hbar \omega_P \rightarrow \hbar \omega_S + \hbar \omega_I \)
- Momentum conservation: (use crystal birefringence) \( \hbar \vec{k}_P \rightarrow \hbar \vec{k}_S + \hbar \vec{k}_I \) “phase matching”
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  “phase matching”

- **Noncollinear angle for maximum bandwidth:**
  (matches group velocities of signal and idler)
  \[ \left( \frac{\partial k_S}{\partial \omega_S} \right) \cos \Omega_{bb} = \left( \frac{\partial k_I}{\partial \omega_I} \right) \]
Noncollinear optical parametric amplifiers (NOPA’s) amplify pulses using a nonlinear three-wave process

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- Noncollinear angle for maximum bandwidth:
  (matches group velocities of signal and idler)

- Ultra-broadband phase matching occurs when stationary to second order:
  \[ \left( \frac{\partial^2 k_S}{\partial \Omega_S^2} \right) \cos \Omega_{\text{magic}} + \left( \frac{\partial^2 k_I}{\partial \Omega_I^2} \right) = k_I \left( \frac{\partial \Omega}{\partial \omega_S} \right)^2 \]
Ultra-broadband phase matching occurs at an inflection point in the phase-matching curves.
Ultra-broadband phase matching occurs at an inflection point in the phase-matching curves.

Locus of stationary points

Phase-matching curves for different $\alpha$

Inflection point

Signal wavelength (nm)

Pump internal angle ($^\circ$)

Phase-matching for DKDP
NOPA’s have many advantages for ultra-intense lasers over traditional gain media (e.g., Ti:sapphire)

<table>
<thead>
<tr>
<th>Property</th>
<th>Benefit</th>
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<tbody>
<tr>
<td>Broadband gain (&gt;170 nm)</td>
<td>Pulse widths &lt;12 fs</td>
</tr>
<tr>
<td>High gain (&gt;10^4)</td>
<td>Amplifiers only few centimeters thick</td>
</tr>
<tr>
<td>Large crystals (&gt;40 cm)</td>
<td>Scale beam size for kilojoule pumping</td>
</tr>
<tr>
<td>Idler removes excess energy</td>
<td>Minimal thermal issues</td>
</tr>
<tr>
<td>Unidirectional gain</td>
<td>(a) No transverse amplified spontaneous emission (ASE)</td>
</tr>
<tr>
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<td>(b) No gain for retroreflections</td>
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NOPA properties place tighter requirements on the pump lasers

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<th>Property</th>
<th>Requirement</th>
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<tr>
<td>Instantaneous gain</td>
<td>Must match pump pulse to signal</td>
</tr>
<tr>
<td>Phase-matched process</td>
<td>Coherent pump with low divergence</td>
</tr>
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The optimum crystal choice depends on the scale of the amplifier, which is set by the aperture and pump energy.

- Many crystal options
- Only KDP and DKDP can be grown large enough for multijoule OPA's.
The optimum crystal choice depends on the scale of the amplifier, which is set by the aperture and pump energy.

- Many crystal options
- A number of pump technologies are available (Ti:Sa, Yb, Nd, etc.)

Small-scale NOPA (~mm, ~mJ)

Large-scale NOPA (~m, ~kJ)

- Only KDP and DKDP can be grown large enough for multijoule OPA's
- Kilojoule pump sources are more limited (Nd:glass, iodine)
The optimum crystal choice depends on the scale of the amplifier, which is set by the aperture and pump energy.

- Many crystal options
- A number of pump technologies are available (Ti:Sa, Yb, Nd, etc.)
- Light wave synthesizer (MPQ)
  - 4.5 fs, 18 TW, $10^{20}$ W/cm$^2$

- Only KDP and DKDP can be grown large enough for multijoule OPA’s
- Kilojoule pump sources are more limited (Nd:glass, iodine)
- Several labs working in this area
  - Rutherford Appleton Laboratory, UK
  - Institute of Applied Physics, Russia
Of the many types of nonlinear media, three crystals are widely used for ultra-broadband NOPA’s.

<table>
<thead>
<tr>
<th>Property</th>
<th>BBO</th>
<th>LBO</th>
<th>DKDP</th>
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<tbody>
<tr>
<td>Name</td>
<td>β-barium borate</td>
<td>Lithium triborate</td>
<td>Potassium dihydrogen phosphate</td>
</tr>
<tr>
<td>Effective nonlinearity ($d_{\text{eff}}, \text{pm/V}$)</td>
<td>2.2</td>
<td>0.82</td>
<td>0.23</td>
</tr>
<tr>
<td>Pump-signal angle</td>
<td>2.2°</td>
<td>1.39°</td>
<td>0.91°</td>
</tr>
<tr>
<td>(α, internal, $\lambda_P = 527 \text{ nm}, \lambda_S = 910 \text{ nm}$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crystal length</td>
<td>4.5 mm</td>
<td>11.5 mm</td>
<td>37.0 mm</td>
</tr>
<tr>
<td>(small-signal gain = $10^4$, $I_P = 5 \text{ GW/cm}^2$)</td>
<td></td>
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<tr>
<td>Gain bandwidth</td>
<td>185 nm</td>
<td>245 nm</td>
<td>178 nm</td>
</tr>
<tr>
<td>(FWHM, small-signal gain = $10^4$)</td>
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<tr>
<td>Maximum aperture size</td>
<td>~20 mm</td>
<td>~50 mm</td>
<td>~500 mm</td>
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</table>
For larger-aperture OPCPA, DKDP provides broadband gain when pumped by frequency-doubled Nd:glass lasers.

DKDP gain (small signal)

\[ \lambda_p = 526.5 \text{ nm} \]

Pump-signal angle = 0.91°

Signal wavelength (nm)

Signal spectrum centered at 910 nm

1050
1000
950
900
850
800
-1000
-500
0
500
1000

Pump angle deviation (μrad)

Small-signal gain

\( I_p = 4 \text{ GW/cm}^2, L = 50 \text{ mm} \)

×10^4

10
8
6
4
2
0
Focal intensities of $10^{24}$ W/cm$^2$ are possible with an OPAL system pumped by OMEGA EP.

An existing OMEGA EP beamline will be used to pump OMEGA EP-OPAL.
The MTW-OPAL system is being built as a stepping-stone to develop and demonstrate scalable technologies.

- **Built**
  - White light → YAG
    - 1.0 nJ
  - BBO
    - 600 nJ
    - 400 μJ
  - BBO
    - 5 mJ
  - Stretch to 1.5 ns
  - BBO
    - 0.5 mJ
  - DKDP
    - 300 mJ
    - 12.5 J

- **Under construction**
  - BBO

- **Completed conceptual design**
  - Nd:YLF: 10 ps, 50 mJ, 5 Hz
  - Nd:glass: 1.5 ns, 60 J, 1 shot/20 min

- **Multi-Terawatt laser (MTW)**
  - E22268

- Optical sync
  - 1.7 nJ
  - 4.0 nJ
  - 7 mJ
  - 35 mJ

- **Other parameters**
  - Fiber CPA: 250 fs, 500-kHz
  - White light → DKDP
    - Compress to 15 fs
  - 7.5 J, 15 fs, $10^{22}$ W/cm²

**System specifications**
- 527 nm
- 810 to 1010 nm
- 1053 nm
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- **Fiber CPA**: 250 fs, 500-kHz, 1.7 μJ
- **Nd:YLF**: 10 ps, 50 mJ, 5 Hz, 4.0 μJ
- **Nd:YLF**: 1.5 ns, 2 J, 5 Hz, 7 mJ
- **White light**
  - **YAG**: 1.0 nJ, 600 nJ, 400 μJ

**Built**
- **BBO**: 35 mJ
- **BBO**: 7 mJ

**Under construction**
- **Stretch to 1.5 ns**: 5 mJ
- **BBO**: 0.5 mJ
- **DKDP**: 300 mJ
- **Compress to 15 fs**: 12.5 J

**Completed conceptual design**
- **7.5 J, 15 fs, 10^{22} \text{ W/cm}^2**
The MTW-OPAL system is being built as a stepping-stone to develop and demonstrate scalable technologies.
A new 1430-ft$^2$ laboratory for MTW-OPAL was recently completed next to the MTW laser and the UFE installed.

MTW-OPAL will be integrated with the existing MTW Laser System to maximize experimental flexibility.
MTW-OPAL is at the midpoint of its development

Today

2009

Pulse width = 13 fs

2011

200-nm stretcher and compressor

2013

Joule-scale DKDP amplifiers, pumped by MTW

2015

2017

Contrast > 10^{12}

System design

Coating development

Prototype testing

Phase control

OPAL demo

15 fs
7.5 J
10^{21} \text{W/cm}^2
Contrast > 10^{10}
Summary/Conclusions

Optical parametric chirped-pulse amplification (OPCPA) offers the potential for intensities exceeding $10^{24}$ W/cm$^2$

- LLE is developing the technologies necessary for an ultra-intense OPCPA system pumped by OMEGA EP
- Large DKDP$^1$ crystals can provide ~200 nm of gain, centered at 910 nm
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  - 15 fs, 7.5 J, $10^{22}$ W/cm$^2$
  - demonstrate technologies that are scalable to a kilojoule system

MTW-OPAL is a stepping stone to the full-scale system, and will provide a focal point for collaborative development and femtosecond experiments.

$^1$Deuterated potassium dihydrogen phosphate
The Light Wave Synthesizer 20 (LWS-20) at MPQ is currently the most intense quasi-single-cycle system.

- Pulse width: 4.5 fs
- Energy: 80 mJ
- Peak power: 18 TW
- Intensity: $\sim 10^{20}$ W/cm$^2$ ($f/1.5$)

- Uses four BBO-based NOPA stages
- Bandwidth from 575 to 1020 nm using two-color pumping
- Repetition rate: 10 Hz

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Ultra-intense OPCPA systems using DKDP are being developed at several facilities

<table>
<thead>
<tr>
<th>PEARL-10(^1)</th>
<th>Vulcan 10 Petawatt(^2)</th>
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<tbody>
<tr>
<td>• Institute of Applied Physics, Russia</td>
<td>• Rutherford Appleton Laboratory, UK</td>
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<tr>
<td>• Goal: 100 J in 20 fs</td>
<td>• Goal: 300 J in 30 fs</td>
</tr>
<tr>
<td>• Upgrading 0.56-PW system (PEARL – PEtawatt pARametric Laser)</td>
<td>• Front end produces 1-J, 150-nm-wide pulses</td>
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<tr>
<td>• Generate 910-nm pulse by seeding a NOPA with an angularly dispersed “idler” at 1250 nm</td>
<td>• Generate 910-nm pulse using the idler from a chirped-collinear geometry</td>
</tr>
</tbody>
</table>

1 V. V. Lozhkarev et al., Laser Phys. Lett. 4, 421 (2007).