Petawatt OPCPA Lasers: Status and Perspectives


Institute of Applied Physics Russian Academy of Science

Introduction

- Compact 0.56 PW laser system
- Scalability to multi-petawatt power

Conclusion
Introduction. OPCPA vs CPA

Advantages of OPCPA:
+ broad gain bandwidth
+ high aperture
+ considerable decrease in thermal loading
+ significantly lower level of ASE
+ very high gain
+ no self-lasing
+ no backscattering from a target

Disadvantages of OPCPA:
– high precision synchronization
– high quality of a pump beam
– short (1ns) pump pulse duration
## Introduction. Petawatt laser systems

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Physics of OPCPA. KD*P vs KDP.

superbroadband phasematching

\[ \frac{1}{527\text{nm}} = \frac{1}{911\text{nm}} + \frac{1}{1250\text{nm}} \]

generated phase matching

\[ \lambda_{\text{signal}} = 2\lambda_{\text{pump}} = 1053\text{nm} \]
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Introduction to PW lasers

- Compact 0.56 PW laser system
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Compact 0.56 PW laser system. Architecture

First phase (TW level)

- Synchronization system
- Cr:Forsterite fs-laser
  - λ=1250nm
  - 2nJ 40 fs
- Stretcher
  - 40 fs → 0.5 ns
  - 1nJ 0.5 ns
- Nd:YLF Q-switch laser
  - λ=1053nm
  - 10mJ 12fs
- Pulse shaper
  - 1mJ 1.5ns
- Two-stage Nd:YLF amplifier
  - 2J 1.5 ns
- OPA I
  - KD*P
  - λ=911nm
  - 0.5ns
- OPA II
  - KD*P
  - λ=1250nm
- Compressor
  - 0.5 ns → 50 fs
  - λ=911 nm
  - 50 mJ 0.5 ns

Second phase (PW level)

- Nd:glass amplifier
  - 300J 1ns
- 2ω
  - 170J 1ns
- OPA III
  - KD*P
  - 10cm dia
  - λ=911 nm
  - 38J 0.5ns
- Compressor
  - 0.5ns → 50 fs
  - 24J 43fs

Freidman G., Andreev N., Ginzburg V., Katin E., Khazanov E., Lozhkarev V., Palashov O., S A Y k I P SPIE 4630 135 146 2002
Compact 0.5 PW laser system:
Key elements of tabletop 300 J Nd:glass laser

- input beam shaping
- spatial filters
- self-focusing suppression
- laser heads
- self-excitation suppression
- second harmonic generation

Martyanov M. A., Khazanov E.A. , Poteomkin A. K.,
Compact 0.56 PW laser system: Nd:glass laser output beam

300J, 1ns

2.44λ/D = 21 μrad

50 μrad

90MM

2.44λ/D = 21 μrad

50 μrad

Trigger is on in direct mode.

CCD Gain = 1.3

Exposure time = 0.403 ms
Compact 0.56 PW laser system. 
Energy characteristics of final OPCPA

- Efficiency, %
- Pulse energy, J

Energy characteristics graph showing:
- Efficiency (%) vs. Pump pulse energy (J)
- Output pulse energy (J)

38 J

2.44λ/D=21μrad
25μrad

compact 0.56 PW laser system.
Compact 0.56 PW laser system.
Compressed pulse

Contrast: $10^8$ (0.5ns window)
$10^4$ (1ps window)


$24 \text{ J} / 43 \text{ fs} = 0.56 \text{ PW}$
Compact 0.56 PW laser system. Compressed pulse
Petawatt OPCPA Lasers: Status and Perspectives

Introduction to PW lasers
- Compact 0.56 PW laser system
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Conclusion
Scalability to multi-petawatt power.
Routes to increase power and contrast

POWER:
+ Pulse duration: \( x_3 \) (15fs instead of 45fs)
+ OPCPA efficiency: \( x_2 \) (40% instead of 20%)
+ Pump power \( x_{1.3} \) (230J instead of 180J)
+ Compressor efficiency \( x_{1.2} \) (79% instead of 66%)

TOTAL: \( x_{11} \) (6PW instead of 0.56PW)

CONTRAST:
Second harmonic generation in KDP crystal

- theory (includes self-focusing) predicts high efficiency
- crystal 100mm diameter and 0.5mm thickness was grown
- experiments are coming soon
Scalability to multi-petaWatt power.
Four started projects.

**VNIEF (Sarov) + IAP, Russia, 2005-2008, 3PW OPCPA**

**Rutherford Lab, UK, 2007-2011, 10PW OPCPA**

**HiPER, pan-European, 2008-2018, 150PW / 2000PW OPCPA**

**ELI, pan-European, 2008-2020, 200PW OPCPA or Ti:sapphire**
Scalability to multi-peta-watt power.
Sarov – N. Novgorod.

First phase (TW level)

Synchronization system

Nd:YLF Q-switch laser
\(\lambda = 1053\text{nm}\)

Cr:Forsterite fs-laser
\(\lambda = 1250\text{nm}\)

CW Yb:fiber pump
10W
\(\lambda = 1050\ldots1080\text{nm}\)

Stretcher
40 fs → 0.5 ns

Two-stage Nd:YLF amplifier

OPA I
KD*P

OPA II
KD*P

Second phase (PW level)

Nd:YLF Q-switch laser
\(\lambda = 1053\text{nm}\)

Pulse shaper

Nd:glass amplifier

\(2\omega\)

Nd:glass amplifier

OPA III
KD*P
10 cm dia

Third phase (2 PW)

Pulse shaper

Nd:YLF amplifier

Nd:YLF amplifier

\(2\omega\)

OPA IV
KD*P
20 cm dia

Compressor

Compressor
Scalability to multi petawatt power.
Sarov – N.Novgorod.

I.A. Belov, O.A. et al. Petawatt laser system of the "Luch" facility
#1. OPCPA at 910 nm in DKDP is the best. No question.

#2. There is only one question.

Q.: The best or one of the best?

A1: See message #1.

A2: Will live and see.
After conclusion... Let’s think about laser ceramics!

**Cr:YAG ceramics**
- **very wide aperture** to amplify chirped pulses to the multikilojoule level,
- **high conversion efficiency** of narrow band Nd:glass laser pulses into chirped pulses,
- **large gain bandwidth** to amplify chirped pulses with less than 20 fs durations

**Nd,Yb:Re$_2$O$_3$ ceramics (Re=Y,Lu,Sc)**
1. **Very wide aperture** to amplify chirped pulses to the multikilojoule level
2. **Large gain bandwidth** to amplify chirped pulses with less than 50 fs durations
3. **High conversion efficiency** due to **direct lamp pumping** (lamps pump Nd and excitation transfers to Yb)

Compact 0.56 PW laser system. Electon acceleration (preliminary results)

Electrons energy spectrum
Numerical simulation
Compact 0.56 PW laser system:
120mm clear aperture OPA

**OPA**
120 mm clear aperture

**SHG**
From front-end system (911nm)

300 J
1054 nm
pump pulse

38J to compressor (911nm)

To diagnostic

300 J
1054 nm

**OPA 3**

180 J
527 nm

SHG
910 nm
Scalability to 100(s) petawatt power

Crazy ideas are welcome!

Cr\textsuperscript{4+}:YAG ceramics (CPA)

### Scalability to multi-petawatt power: Crazy ideas are welcome!

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Physics of OPCPA. Wideband phase-matching

\[ \omega_3 = \omega_1 + \omega_2 \]

\[ \omega_1 = \omega_{10} + \Omega(t) \]
\[ \omega_2 = \omega_{20} - \Omega(t) \]

\[ k_{2x}(\omega_2) = k_{3x} \]

\[ \Delta \vec{k}(\Omega) = \Delta \vec{k}(\Omega) \cdot \vec{z}_0 \]

\[ \Delta k(\Omega) \equiv \Delta k(0) - \left( \frac{dk_1}{d\omega} + \frac{dk_{2z}}{d\omega} \right) \Omega - \frac{1}{2} \left( \frac{d^2 k_1}{d\omega^2} + \frac{d^2 k_{2z}}{d\omega^2} \right) \Omega^2 - 0(\Omega^3) = 0 \]

phase-matching

\[ k_3 = k_1(0) + k_2(0) \]

super-wideband phase-matching

\[ V_1 g = V_2 g \cdot \cos \varphi_{12} \]