A high-energy and highly repetitive fs/ps short pulse laser production using OPCPA with ns Beam Combined Dream Laser pumping for fast/shock ignitions

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Motivation

• To Achieve laser inertial fusion energy (LIFE), we need a laser driver:
  • 10 Hz repetition rate
  • Pulse energy per beam line > 2.5 kJ
  • Pulse width
    • 5~10ns for compression
    • 1~15 ps for fast ignition, 300~500 ps for shock ignition
• Solutions to increase the output pulse energy/power with high rep. rate:
  • LD pumping
  • High thermal conductivity laser media (Ceramic laser materials)
  • Cryogenically cooled ceramic lasers (Yb:YAG, …., many candidates are being developed)
• Cooling problem(thermal) and parasitic oscillation
  • limit the size of the laser media > limit attainable output energy/power
  • Beam combination of available lasers;
    • extends the attainable energy/power → Energetic ns Beam Combined Dream Laser
• Solution to generate an igniting short pulse laser driver:
  • OPCPA using a ns Beam Combined Dream Laser
  • Beam combination of short pulse lasers
Laser Inertial fusion facility: NIF

- World’s largest laser facility: 5.4 MJ @ 1.05 μm / 1.8 MJ @ 0.35 μm
  - At least, 25 kJ × 200 beam lines are required for IFE
- Low repetition rate: 1~2 shots/day
  - However, 10 Hz repetition rate is required for IFE plant
Several methods of the inertial fusion ignition

Compression by laser driver

Implosion

Shock ignition

Central ignition

Burning

Fast ignition

Heating & igniting by ultrafast laser (blue)

Impacting by shock pulse (green)

*Shock ignition or fast ignition can reduce the required pulse energy of laser driver from 5 MJ to 500 kJ.
Comparison of ignition methods

<table>
<thead>
<tr>
<th>types of ignition method</th>
<th>Estimation value of required pulse energy</th>
<th>note</th>
<th>Facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ns laser</td>
<td>ps/fs laser</td>
<td></td>
</tr>
<tr>
<td>Central ignition</td>
<td>5.4 MJ @ 1.05 μm</td>
<td>-</td>
<td>Most simple, but high pulse energy is required</td>
</tr>
<tr>
<td></td>
<td>1.8 MJ @ 0.35 μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast ignition</td>
<td>500 kJ @ 1.06 μm</td>
<td>100 kJ @ 0.53 μm /1~10ps</td>
<td>special target(cone-inserted target) is required to deliver the igniting laser into the fuel</td>
</tr>
<tr>
<td></td>
<td>180 kJ @ 0.35 μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shock ignition</td>
<td>500 kJ @ 1.06 μm</td>
<td>100kJ @ 0.35μm /300~500ps</td>
<td>Single laser can be utilized for compression and ignition</td>
</tr>
<tr>
<td></td>
<td>180 kJ @ 0.35 μm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Most challenging issues in LFE

- High Rep. Rate Laser (2.5kJ@10Hz module)
- (option for Fast/shock ignition)
  High Rep. Rate ps/fs Laser (pulse width: 1~500 ps)
- Target injection (< 20μm@400m/s@5meters)
- Protection of windows from explosion debris

Resolved by Coherent Beam Combination by self-phase controlled SBS-PCM
Tactics to achieve IFE with the advanced ignition concepts

- **2.5 kJ @ 10 Hz, ~ns laser driver** for compression
  - by coherent beam combining using SBS-PCMs

- **100kJ @ 10 Hz, fs/ps laser** for fast ignition/shock ignition
  - through OPCPA pumped by ns Beam Combination dream Laser

- **Target injection** ( <20 μm @ 400 m/s @ 5 m)
  - Self navigation technique using SBS-PCMs
High rep. rate fs/ps laser can be produced by OPCPA using ns high rep. rate laser.
Beam combination using self-controlled SBS-PCM: easy, proven, and scalable

• **Self-phase-controlled SBS-PCM:**
  – Most simple structure
  – only SBS medium cell and concave mirror

• **Experimentally proved:**
  – Coherent 4 beam combination system (~100mJ @ 10 Hz) is successfully demonstrated

• **Easily scalable**
  – By increasing additional gain medium, we can yield pulse energy we want
Beam combination and its problems

Cooling problem + parasitic oscillation

Large-size laser medium

Wavefront distortion

Easy cooling

Piston error
# Ways of clean-up of wave-front distortion

<table>
<thead>
<tr>
<th>Loss of Energy</th>
<th>Spatial filtering</th>
<th>Adaptive Optics</th>
<th>Phase Conjugate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Depends on the beam quality</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td><strong>system</strong></td>
<td>Simple</td>
<td>Complicated</td>
<td>Most simple</td>
</tr>
<tr>
<td><strong>Input energy</strong></td>
<td>No limit</td>
<td>No limit</td>
<td>No limit</td>
</tr>
<tr>
<td><strong>Piston error correction</strong></td>
<td>OK</td>
<td>OK</td>
<td>impossible before 2003*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phase Conjugate</th>
<th>SBS</th>
<th>4Wave Mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td><strong>system</strong></td>
<td>Most simple</td>
<td>Complicated</td>
</tr>
<tr>
<td><strong>Input energy</strong></td>
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</tr>
<tr>
<td><strong>Piston error correction</strong></td>
<td>OK</td>
<td>OK</td>
</tr>
</tbody>
</table>

* Random Piston Error of SBS-PCM
  - inherent problem of SBS,
  - but it was resolved by H. J. Kong in 2003 by the self-phase-control technique
Phase conjugate mirror

Conventional mirror

\[ e^{i\phi(\vec{r})} \]

Phase conjugate mirror

\[ e^{-i\phi(\vec{r})} \]
Practical Application of SBS-PCM

Master oscillator power amplification (MOPA) with phase conjugate mirror (PCM)
Image reconstruction by SBS-PCM

PBS: Polarizing beam splitter; BS: Beam splitter; QWP: Quarter wave plate;
 CX1, 2, PLCC: Lenses
Image reconstruction by SBS-PCM

Conventional mirror

Without aperture

SBS-PCM

Rose shaped aperture
Beam combinations

- (a) Side-by-side beam combination
- (b) Tiled aperture coherent beam combination
- (c) Filled aperture coherent beam combination
- (d) Serial wavelength beam combination
- (e) Parallel wavelength beam combination
Beam combination laser system using SBS-PCMs

Wave-front dividing method

WD M × M Amp array
Beam combination laser system using SBS-PCMs

Amplitude dividing method

AD $M \times M$ Amp array
Previously developed phase control methods

1. **Overlapping** the SBS focal points locks the phases of the beams.
2. Phase locking by **back seeding** the Stokes shifted beam, which locks the phase of the PC wave.

---

**a)** Overlap of two focal points  

**b)** Back-seeding of Stokes wave  

---

*Impractical for many beams > 4*  
*PC can be broken by back seeding beam  
No PC anymore*
Brillouin-enhanced four-wave mixing (BEFWM)


Good for controlling phase

Too complicated optics
Phase of SBS wave

\[ \phi_{SBS} = \phi_{laser} - \phi_{acoustic} \]

\( \phi_{acoustic} \) is random for it is originated from noise. If \( \phi_{acoustic} \) is controlled, we can control \( \phi_{SBS} \).
pulsed duration to be long compared with the SBS onset time and intercell transit time. Similarly, for a coherent interaction it is necessary for the laser coherence length to be at least twice the total length of the two-cell system. If the intercell transit time is long, then there will be a lengthy delay before the amplifier is seeded and power limiting becomes effective. For this reason it is desirable to use a relatively compact two-cell geometry.

A further feature demonstrated by the simulations but also observed experimentally at high powers is the ability to achieve greater than unity reflectivity on a transient basis. This overshoot by the Stokes radiation can be explained by storage of radiation in the two-cell system. The excess of Stokes power over the input pump will only be temporary since the severe depletion of the pump will reduce the seeding signal, resulting in an overshoot for a time of the order of twice the intercell transit time. The amount of overshoot is dependent on the gain of the amplifier and on the intercell losses. For low losses, the seeding level can be high, leading to a substantial overshoot.

The performance of the generator cell could be improved by the introduction of optical feedback, which has been shown to reduce the threshold and increase the phase conjugate fidelity of the SBS process [7.6], as described previously.

7.5 Laser beam combining using SBS

In the normal SBS configuration a single pump beam is incident upon the SBS medium, and the Stokes scattered output beam is generated by amplification of noise. This SBS scattered field will have a random overall phase since it starts from statistical noise and, in addition, this phase has been shown to fluctuate randomly in a time of the order of several times the phonon lifetime [7.14]. The SBS reflection, therefore, has no absolute temporal phase reference. As a consequence, if two beams are conjugated by SBS in separate interaction volumes the two Stokes beams will have a phase difference that is random and unrelated to the phase difference of the pump beams. Basov et al. [7.15] first predicted this random phase difference and several groups demonstrated its existence [7.16–7.18]. If the random phase difference in the Stokes beams is to be avoided an absolute phase reference must be created. This can be accomplished by several methods.

7.5.1 Laser beam combining using spatial overlap in SBS

Consider the case where two or more pump beams are overlapped in the same interaction volume. They appear to the SBS process as a single, but highly aberrated, beam with the relative phase between the beams appearing as an aberrated wave front. The standard mechanism that phase conjugate a
“Self-phase control” method

- Feed back mirror > Counter propagating beams > Standing wave > Density modulation
- Standing density modulation locks the ignition position of the moving Bragg grating.
- The Bragg grating locks the phase of the SBS wave.
- Phase controlling of SBS wave is possible by positioning the feed back mirror.

(a) Concentric type
(b) Confocal type
Reflectivity and breakdown probability depending on the laser mode of SBS-PCM with FC-75

Single mode pumping
(Δν~120MHz, Γ=350MHz)
(No break down)

Multi mode pumping
(Δν~30GHz, Γ=350MHz)
(Break down occurs)

Experimental setup for the wave-front dividing 4-beam combination

PB1&PBS2, polarizing beam splitters; HWP1&HWP2, half wave plate; P1, P2&P3, 45 degree prisms; BS, beam splitter; W, wedged window; FR1, FR2, FR3&FR4, Faraday rotators; C1, C2, C3&C4, concave mirrors; PZT1, PZT2&PZT3, piezoelectric translators.

4-beam output profile & Interference patterns

4-beam combined output profile

Interference patterns at CCD camera

0: Reference beam

Beam Energy – AMP off case

- **Input energy**: 32.2 ± 0.3 mJ
- **Output energy**
  - AMP off: 9.9 ± 0.5 mJ (reflected by SBS-PCMs)
Phase fluctuation without amplifier operation

\[ \Delta \Phi_{01} \]

\[ \Delta \Phi_{02} \]

\[ \Delta \Phi_{03} \]

\[ \Delta \Phi_{04} \]

SD: \( \lambda/43.4 \)

SD: \( \lambda/35.8 \)

SD: \( \lambda/36.3 \)

SD: \( \lambda/86.2 \)

\[ \begin{align*}
\text{Phase difference (degree)} \\
\text{Count of shots}
\end{align*} \]

Beam Energy – AMP on case

- **Input energy**: 32.2 ± 0.3 mJ
- **Output energy**
  - AMP off: 169 ± 6 mJ (gain: 5.3)
Phase fluctuation with amplifier operation

\Delta \Phi_{01}

\Delta \Phi_{02}

\Delta \Phi_{03}

\Delta \Phi_{04}

Kumgang (金鋼) laser: 0.1J@10ns@10kHz laser modules and beam combination for 4 kW using SBS-PCMs
Laser System Configuration

Front-End
- 1064nm/10kHz
- Single frequency
- Tunable
- Output > 0.3mJ/pulse
- (3W @ 10kHz)

Pre Amp
- Nd:YAG Rod
- Output > 200W

Coherent Beam Divider/Combiner

Main Amp I (SBS-PCM)
- Nd:YAG Rod
- SBS-PCM
- Output > 1 kW

Main Amp II (SBS-PCM)

Main Amp III (SBS-PCM)

Main Amp IV (SBS-PCM)

Output 4kW @ 10kHz (0.4J per pulse)
Front-End Laser System
Hybrid Front-End Laser System Design Requirement

1064nm DFB Diode Laser → AOM Pulse Shaper → Yb-doped Fiber Amplifier

10kHz Master Oscillator

DFB CW diode laser
- Tunable 1064-1065nm
- Single frequency linewidth

AOM Pulse shaper
- 10kHz-10ns Gaussian-like pulse
- High pulse contrast ratio

Yb-doped fiber amplifier
- Yb-doped PM gain fiber
- 976nm LD pump
- All PM fiber optic

Diode-pumped 10kHz Nd:YAG Regenerative Amplifier
- Output > 5W (0.5mJ)
- Rep rate 10kHz
- Pulsewidth ~ 10ns
- Single frequency < 100MHz
Hybrid Front-End Laser Layout

CW Diode Laser (single freq)

Pump LD (976nm)

FC/APC

AOM

WDM

Yb-doped fiber amplifier

Band pass filter (1064+/−1nm)

10kHz Master Oscillator (seeder)

10kHz Nd:YAG Regenerative Amplifier

Injection seeding

10kHz, Single frequency output
Master Oscillator Setup

CW DFB Diode Laser (single freq ~1MHz)

Pump LD (976nm)

AOM pulse shaper

AO rf driver

FC/APC

PM fiber

WDM

10kHz/10ns pulse

Yb-doped gain fiber 1.5m

PM 6/125um

Band pass filter (1064+/-1nm)

Output 10nJ @10kHz

Master Oscillator

Band pass filter

Yb-doped fiber amplifier (Gain>50)

x=spliced

Laser diode controller (Current & TEC driver)

Digital pulse & delay generator

AO: acousto-optic modulator
WDM: Wavelength division multiplexer
DFB Laser Diode Wavelength TEC Temperature Tuning

Temp. Coefficient = +0.076nm/C

@ LD Current=100.0mA
DFB Laser Diode Linewidth Measurement (Scanning Fabry-Perot Interferometer)

F-P spectrum

FSR=1500MHz

FWHM linewidth $\Delta v < 10$MHz
Temp scan $\sim 200$MHz/0.01C
(F-P resolution=7.5MHz)
Master Oscillator Spectrum

Central wavelength = 1064.5 nm
Master Oscillator Output Pulse @ 10kHz

MO output pulse

~280ns

AOM pulse shaper trigger signal

FWHM 9.5ns +/- 0.3ns
Master Oscillator Beam Profile
Nd:YAG Regenerative Amplifier (RA)

10 kHz Nd:YAG Regenerative Amplifier


PC voltage

Seed injection

RA ejection

Seed beam 10 kHz/10 ns

RA Cavity L = 2.8 m
Round-trip time = 18 ns

OUTPUT
Nd:YAG RA Output Power & Stability

5.100W

5.12 W ± 25.0 mW (σ = 0.49 % rms)  
(0.51 mJ per pulse, 10 kHz)  
during 1 hour
Nd:YAG RA Output Pulse

Output pulse ~35 round-trips in RA cavity
Variable pulsewidth 5-10 ns (typical~8.5 ns)
Pulse contrast ratio > 50:1
Nd:YAG RA Output beam profile
Nd:YAG RA Linewidth Measurement (Fabry-Perot Spectrum Analyzer)

Single frequency F-P fringe

FSR=7.5 GHz
Nd:YAG RA Linewidth Measurement
(Scanning Fabry-Perot Interferometer)

Single frequency linewidth
\[ \Delta \nu = 60 \text{ MHz} \pm 5 \text{ MHz} \]
Nd:YAG rod Pre-Amplifier
Nd:YAG Gain Module Design for Pre-AMP

Nd:YAG rod Gain Module (GM) for Pre-AMP

- Wavelength 1064 nm
- Nd:YAG rod- φ4.5 mm x 96 mm
- CW diode-stack side-pumped
- Pump power 1 kW max @808 nm
- CW output power 500 W max (Short test cavity, unpolarized)
- DI water-cooled

<table>
<thead>
<tr>
<th>Gain Module*</th>
<th>Nd:YAG Rod</th>
<th>Pump LD (max Power)</th>
<th>CW Output*</th>
</tr>
</thead>
<tbody>
<tr>
<td>HiWatt1000</td>
<td>4.5 mm dia, 0.6%</td>
<td>200 W x 5ea (1 kW)</td>
<td>&gt; 400 W, MM</td>
</tr>
</tbody>
</table>

*Laser Spectronix
Nd:YAG Gain Module
Short Test Cavity CW Output Power

Nd:YAG Gain Module HiWatt-1000

Slope efficiency 62%

Short Test Cavity

L = 160 mm

GM

HR

OC(T=30%)
Pre-Amplifier
Double-pass, 2 Gain Modules

- Thermal lensing compensation → Image relay
- Thermal birefringence compensation → two rods arrangement & 90-degree polarization rotation by quartz rotator

PBS-polarizing beam splitter, RL-Image relay lens, QR-quartz rotator, FR-Faraday rotator, HW-Half waveplate (for input power adjustment)
Pre-Amplifier
Double-pass, 3 Gain Modules

PBS-polarizing beam splitter, RL-Image relay lens, QR-quartz rotator, FR-Faraday rotator, HW-Half waveplate (for input power adjustment)

- Thermal lensing compensation $\rightarrow$ Image relay
- Thermal birefringence compensation $\rightarrow$ two rods arrangement & 90-degree polarization rotation by quartz rotator
Pre-Amplifier Performance
Double-pass Amplification

![Graph showing the relationship between input and output power with 3x GM and 2x GM labels.]
Pre-Amplifier Performance: 2-GM Output Power Stability

87.70W

Channel A Measurement

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Min</td>
<td>86.20W</td>
</tr>
<tr>
<td>Max</td>
<td>98.50W</td>
</tr>
<tr>
<td>Average</td>
<td>87.36W</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>336.9mW</td>
</tr>
<tr>
<td>Overrange</td>
<td>0</td>
</tr>
</tbody>
</table>

< 0.38% rms (30 min)
Pre-Amplifier Performance: 3-GM Output Power Stability

< 0.28% rms (5 min.)
Pre-Amplifier Performance: Output Beam Profile

62.50W
Nd:YAG rod Main Amplifier
Nd:YAG Gain Module Design for Main Amplifier

Nd:YAG rod Gain Module (GM) for Main Amplifier

- Wavelength 1064 nm
- Nd:YAG rod- $\phi$ 6.35 mm x 148 mm
- LD pumping length- 96 mm
- CW diode-stack side-pumped
- Pump power 2 kW max @ 808 nm
- CW output power 1 kW max (short test cavity, unpolarized)
- DI water-cooled

<table>
<thead>
<tr>
<th>Gain module</th>
<th>Nd:YAG Rod</th>
<th>Pump LD (max Power)</th>
<th>CW Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>HiWatt 2000*</td>
<td>$\phi$ 6.3 mm, 0.6%</td>
<td>400 W x 5ea (2 kW)</td>
<td>&gt; 800 W, MM</td>
</tr>
</tbody>
</table>

*Laser Spectronix
Nd:YAG Gain Module
Short Test Cavity CW Output Power

- HiWatt-2000 Nd:YAG Gain Module
- Slope efficiency = 51%
- Short Test Cavity
  - L = 220 mm
  - GM
  - HR
  - OC(T=30%)

Output Power (W) vs. Diode Pump Power (W)
Nd:YAG 1X Gain Module:
Small Signal Gain Measurement

OUTPUT

Nd:YAG GM (HiWatt-2000)

1.0 W, 10 kHz, 8.5 ns

PBS

HW

Front-End Laser

OUTPUT

Output Power (W), Gain

GM Pump Power (W)

Output power

Gain
Nd:YAG 1XGain Module
Single-pass (1P) Amplification

Front-End Laser

Pre-AMP

Nd:YAG Gain Module

Nd:YAG Gain Module

Nd:YAG GM (HiWatt-2000)

OUTPUT

Nd:YAG gain module
1-pass amplification

> 5W, 10 kHz, 8.5 ns
Nd:YAG 1XGain Module: Single-pass(1P) Amplification

GM pump power 1520 W

GM pump power 1280 W
Main-Amp 4XGain Modules
Single-pass (1P) Amplification

Pre-AMP

Main-AMP module

Front-End Laser

Nd:YAG Gain Module
Nd:YAG Gain Module
Nd:YAG Gain Module
Nd:YAG Gain Module

Pre-AMP

Main-AMP module
Master oscillator
LD Temperature VS. main amp 4XGM LD current

@Main amp Input power: 5 w
Main amp 4XGM 1P power test

*Master osc LD temperature: 21.5°C, 22°C
*Main Amp GM LD current: 45 A, 48 A, 50 A

@ 21.5 °C -> 1064.47 nm
@ 22 °C -> 1064.51 nm
Main amp 4XGM 1P power test

*Master osc LD temperature: 21.5°C, 22°C, 22.5°C
*Main Amp GM LD current: 50 A
Main-AMP 4XGain Modules: Single-pass(1P) Output Power & Stability

1.075kW

1070 W ± 10 W (σ=0.93%) during 5 minutes
Main-Amp 2 Gain Modules
Double-pass Amplification

Front-End Laser

Pre-AMP

Main-AMP module
Main-Amp 2XGain Modules
Single & Double-pass Amplification

![Graph showing the relationship between input power and output power for single and double-pass amplification. The graph illustrates that double-pass amplification increases the output power by approximately 1.57 times compared to single-pass amplification.](image-url)
LD laser oscillator module

- CW DFB Diode Laser (single freq ~1MHz)
- Pump LD (976nm)
- LD oscillator (30 mW)
- LD driver
- AO rf driver
- Pumping LD
- Acoustic Optical Modulator (AOM)
- Yb-doped gain fiber 1.5m PM 6/125um
- Master Oscillator
- Yb-doped fiber amplifier (Gain>50)
- Band pass filter (1064±/-1nm)

Pumping LD:
- 30mW @1064nm
- 10kHz/10ns pulse

LD oscillator (30 mW):
- 10kHz pulse slicing

Diagram:
- AO pulse shaper
- Yb-doped gain fiber
- Band pass filter
- Master Oscillator
- LD driver
- Pumping LD
- CW DFB Diode Laser
- pump laser (976nm)
- LD oscillator (30 mW)
Regenerative Amplifier setup

Hybrid seed laser = LD master oscillator + Fiber amp
FI, Faraday isolator; HWP1~2, half wave plates;
FR, Faraday rotator; PBS, Polarizing beam splitter;
TFP1~2, Thin film polarizers; QWP, quarter wave plate;
PC, Pockels cell; GM, gain module;
HR, High Reflector; HRCC, High reflector(concave);
Pre-AMP setup
GM, Gain module;
RL, Relay image lens;
HR, High Reflector;
FR, Faraday rotator;
PBS, Polarization beam splitter;
ISO, Isolator
4 Main Amps
Critical power of SBS-PCMs

• If Kumgang laser is successfully demonstrated, we can apply the SBS-PCM to 100 J @ 10 Hz (1 kW), because the load to SBS-PCMs of Kumgang laser is same as 1 kW (0.1 J @ 1 kHz).

• Furthermore, We expect that SBS-PCMs can be utilized at the output power of 10 kW.
Schematic of proposed LFE driver
(2.5 kJ @ 10 Hz module)
Plan for laser fusion driver configuration

<table>
<thead>
<tr>
<th>Plan</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>For 2.5 kJ @ 10 Hz,</td>
<td></td>
</tr>
<tr>
<td>- 25 × 100 J</td>
<td></td>
</tr>
<tr>
<td>- 3 × 1 kJ beam combinations</td>
<td>available</td>
</tr>
<tr>
<td>For 25 kJ @ 10 Hz (NIF Class)</td>
<td></td>
</tr>
<tr>
<td>- 250 × 100 J</td>
<td></td>
</tr>
<tr>
<td>- or 25 × 1 kJ beam combinations are available</td>
<td></td>
</tr>
</tbody>
</table>
OPA: Optical Parametric Amplification

Pump beam

Signal beam

Amplified signal

Depleted pump

Nonlinear crystal
CPA: Chirped Pulse Amplification

Initial short pulse

A pair of gratings disperses the spectrum and stretches the pulse by a factor of a thousand

The pulse is now long and low power, safe for amplification

Power amplifiers

High energy pulse after amplification

A second pair of gratings reverses the dispersion of the first pair, and recompresses the pulse.

Resulting high-energy, ultrashort pulse
High rep rate high energy fs/ps laser by OPCPA

Exa-watt laser concept based on broadband OPA pumped by multiple beams

Amplified signal (Uniform phase)

Multiple pump beams with different phases

Broadband signal

Partially deuterated KDP

Experimental setup for the OPA pumped by 2x1 beams

WP: waveplate; PL: polarizer; EXP: beam expander; P1 and P2: prisms that split the pump beam; P3: prism for control of relative phase; RPP: random phase plate; AP: aperture; DM: dichroic mirror; GLP: Glan laser prism.

The OPA pumped by 2x1 beam


Interferogram of the two pump beams obtained with a reference beam with uniform phase distribution and far-field pattern of the pump, the idler, and the amplified signal
The OPA pumped by 2x1 beam

Strehl ratio of far-field pattern of the pump (closed square), amplified signal (closed circle), and idler (open triangle).

Experimental setup for the OPA pumped by multi beams

WP: waveplate; PL: polarizer; EXP: beam expander; P1 and P2: prisms that split the pump beam; P3: prism for control of relative phase; RPP: random phase plate; AP: aperture; DM: dichroic mirror; GLP: Glan laser prism.

The OPA pumped by multi beams

Near field interferogram with reference beam (uniform phase)

Far-field

OPA material: Wide band DKDP (13\% D to H)

Random phase plate (Size: 40mm x 40mm)

1.5mm

Pump beam

OPA output beam

The OPA pumped by multi beams


Encircled energy of the amplified signal with respect to the aperture diameter measured in a unit of $F\lambda$ ($F$: f number of the focusing optics, $\lambda$: wavelength)
Nonlinear crystals for OPCPA

<table>
<thead>
<tr>
<th>Material</th>
<th>YCOB</th>
<th>DKDP</th>
<th>LBO</th>
<th>BBO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod ($D_{eff}$)</td>
<td>0.952</td>
<td>0.225</td>
<td>0.828</td>
<td>2.2</td>
</tr>
<tr>
<td>Thermal conductivity (W/m*K)</td>
<td>2.68</td>
<td>1.045</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Temperature acceptance (K*cm)</td>
<td>105</td>
<td>11.3</td>
<td>39.7</td>
<td>55</td>
</tr>
<tr>
<td>Angular acceptance (mrad*cm)</td>
<td>0.8</td>
<td>2.5</td>
<td>7</td>
<td>1.0</td>
</tr>
<tr>
<td>Damage threshold (J<em>cm^{-2} ; GW</em>cm^{-2})</td>
<td>29.1 / 22.4</td>
<td>10.9 / 8.4</td>
<td>24.6 / 18.9</td>
<td>15.6 /</td>
</tr>
<tr>
<td>Maximum aperture size (mm)</td>
<td>~80</td>
<td>~500</td>
<td>~50</td>
<td>~20</td>
</tr>
</tbody>
</table>

OPCPA system for ignition lasers

- **ns beam combination laser**
  - 25 kJ@10 Hz

- **Temporal sync**

- **Nonlinear crystal**
  - (Second Harmonic Generation)

- **10 beams of 25 kJ@10 Hz, 1064nm**

- **10 beams of 15 kJ@10 Hz, 532nm**

- **Pump Beam 1**
- **Pump Beam 2**
- **Pump Beam 3**

- **OPA 1**
- **OPA 2**
- **OPA 3**

- **Amplified signal beam**

- **Compressor**
  - 60 kJ@10 Hz
Future Plans

1st step ($5M, 3.5 years from Sept. of 2012)
- 4 Beam combination
  - 0.1 J @ 10 kHz

2nd step (3 years)
- 10 X 10 Beam combination
  - 0.4 J @ 10 kHz

2nd step (3-5 years)
- 100 J ~ 1 kJ @ 10 Hz
- 4 Beam combination
- 400 J ~ 4 kJ @ 10 Hz

- 10 X 10 Beam combination
- 10 kJ ~ 100 kJ @ 10 Hz
- > 100 kW

- Laser machining by Hologram
- Laser peening
- n/p generator
- Laser Fusion
- Etc.
Conclusion

• To achieve the inertial fusion energy (IFE), Beam combination is one of the most promising techniques for the laser fusion driver
  – ns laser driver for compression: available with **ns Coherently beam combined Dream Laser** using **SBS-PCMs**
  – ps/fs laser for ignition:
    • available with
      – **OPCPA** using **ns Beam Combined Dream Laser as a pumping source**
      – or **Beam combination of ps/fs lasers**

• **Real OPCPA Laser Fusion Driver system can be developed after Kumgang Laser is successfully demonstrated.**
Thank you for your attention.
Future Works

- With new amplifiers, the 4 beam combined output energy is expected to be around 2,000mJ (4×500mJ) at 10 Hz repetition rate.
  
  ✓ For AD and WD

- For the WD beam combination
  
  ✓ Beam-quality improvement by
    
    ➢ image relays,
    
    ➢ serrated apertures
Publications


Publications


### Publications


Publications


34. H. J. Kong, S. Park, S. Cha, and J. S. Kim, “0.4 J/10 ns/10 kHz-4 kW coherent beam combined laser using stimulated Brillouin scattering phase conjugation mirrors for industrial applications”, Physica Status Solidi (c), 10(6), 962-966, 2013

Experimental setup for 4-pass amplification

SA: serrated aperture  FR: Faraday rotators
AMP: amplifier       HWP: half-wave-plate
M: mirror           EM1,2: energy meters
BS: beam splitter   CAM: camera
Serrated aperture

- Inner diameter of aperture = 5.25mm
- Height of the tooth = 1.25mm
- Number of teeth = 80
- Base material: Sodalime glass
- Crom coating
- Thickness of crom coating: = 100μm

Inner diameter 5.25mm
Tooth height 1.25mm
Experimental results: Comparing between circular serrated aperture and circular hard aperture.
Simulation condition

- SA
- 0.5m
- 1.5m
- 1.0m
Simulation result

Bema pattern at 0.5 m after Serrated aperture
Yellow circle: 8mm diameter
Simulation result

Bema pattern at 1.0 m after Serrated aperture
Yellow circle : 8mm diameter
Simulation result

Bema pattern at 1.5 m after Serrated aperture
Yellow circle: 8mm diameter
Gain of 1-pass, 2-pass, and 4-pass output

Electrical input signal (J) vs. Output Energy (mJ)

- 1-pass
- 2-pass SBS-PCM
- 2-pass Mirror
- 4-pass Mirror + SBS-PCM
1-pass gain

Flashlamp electrical input energy 86.4J
Small signal energy 0.196mJ, output energy 3.37mJ, gain =17.44
2-pass (SBS-PCM) gain

Flashlamp electrical input energy 86.4J
Small signal energy 0.183mJ, output energy 32.06mJ, gain = 175.3
Flashlamp electrical input energy 86.4J  
Small signal energy 0.186mJ, output energy 142.6mJ, gain = 765.9
Small signal input energy = 0.191 mJ

Flashlamp electrical input energy 86.4 J
Small signal energy 0.191 mJ, output energy 499.1 mJ, gain = 2600.9
4-pass output beam patterns

Before Amplifier

After 2-pass amp, before SBS-PCM

FL energy 29.4J

38.4J

48.6J

60.0J

72.6J

86.4J
Experimental setup for the long-term phase stabilization

\[ I_1 = \frac{1}{2} I_0 (1 + \sin \Delta \phi) \]

\[ I_2 = \frac{1}{2} I_0 (1 - \sin \Delta \phi) \]

\[ I_{out} = \frac{1}{2} I_{max} (1 + \cos \Delta \phi) \]

Long-term phase fluctuation – No PZT control case


Long-term stabilized result – PZT control case

SD=0.0214 $\lambda$ (=\(\lambda/46.7\))

SD=4.61%

Max: 80.9 mJ
Med: 77.1 mJ
Mean: 76.3 mJ

(Reflectivity fluctuation: 1.34% & 1.42%)

Experimental setup for the long-term phase stabilization with amplifiers

Experimental Setup for the Long Term Phase Stabilization (Amp operation case)

Long-term phase fluctuation – No PZT control case

Long-term stabilized result – PZT control case

SD=0.0445 \( \lambda \) (=\( \lambda \)/22.5)

SD=7.18%

Max: 228 mJ
Med: 211 mJ
Mean: 208 mJ

Experimental setup for the amplitude dividing 4-beam combination

4-beam combined output energy

6.16% Energy fluctuation

Pre-pulse technique for waveform preservation of SBS waves
1. To avoid the deformation of the waveform, the pre-pulse technique has been developed.

2. At first, the laser pulse is divided into two pulses with delay time. (main pulse + pre-pulse, $E_{\text{main pulse}} > E_{\text{pre-pulse}} \sim E_{\text{threshold}}$)

3. Pre-pulse which is incident on the SBS cell prior to the main pulse creates the acoustic grating.

4. Therefore, the main pulse does not lose its energy for the acoustic grating generation.

5. Waveform of the reflected main pulse can be preserved.
• The SBS wave has a steep rising edge because it consumes its front part energy to generate the acoustic grating.
• This steep rising edge causes the optical breakdown in the SBS cell 2.
Pre-pulse technique

- HPs, half-wave plates; PBSs, polarizing beam splitters; ISO, optical isolator; FRs, Faraday rotators; QP, quarter-wave plate; M, mirror; L, focusing lens; PD, photodiode
Waveforms of the SBS wave according to the pre-pulse energy

**Delay time: 3 ns**

(a) $E_{\text{pre}}=0$

(b) $E_{\text{pre}}=6 \text{mJ}$

(c) $E_{\text{pre}}=7 \text{mJ}$

(d) $E_{\text{pre}} \geq 8 \text{mJ}$

**Delay time: 8 ns**

(a) $E_{\text{pre}}=0 \text{mJ}$

(b) $E_{\text{pre}}=2 \text{mJ}$

(c) $E_{\text{pre}}=2.5 \text{mJ}$

(d) $E_{\text{pre}} \geq 3 \text{mJ}$

Waveforms of the SBS wave according to the pre-pulse energy

Delay time: 15 ns

(a) $E_{\text{pre}} = 0 \text{mJ}$  
(b) $E_{\text{pre}} = 1.5 \text{mJ}$  
(c) $E_{\text{pre}} = 1.8 \text{mJ}$  
(d) $E_{\text{pre}} \geq 2 \text{mJ}$

Delay time: 17 ns

(a) $E_{\text{pre}} = 2 \text{mJ}$  
(b) $E_{\text{pre}} = 2.5 \text{mJ}$  
(c) $E_{\text{pre}} = 3 \text{mJ}$  
(d) $E_{\text{pre}} \geq 4 \text{mJ}$

Required pre-pulse energy vs. the delay time