A High-Resolution, Adaptive Beam-Shaping (HRABS) System in a Multi-Terawatt Laser

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Summary

A high-resolution beam-shaping system (HRABS) was demonstrated in a multi-terawatt laser

- Fluence spatial variations and wavefront errors limit the laser-system energy and focusable power density on target
  - HRABS improves both using a spatial-light modulator in a closed loop

- Beam shaping was demonstrated in an OPCPA-based multi-terawatt laser
  - peak-to-mean of fluence is reduced by about a factor of 2
  - HRABS is ready to be implemented in OMEGA EP long-pulse beamlines

- Damage threshold of the SLM is 230 mJ/cm²

HRABS improves the performance of high-power laser systems.

An electrically addressed SLM and a high-resolution Shack-Hartmann wavefront sensor are primary devices.

**Hamamatsu LCOS SLM (X10468)**
- **Area**: $12 \times 16 \text{ mm}^2$
- **Control points**: $600 \times 792 (20 \mu \text{m})$
- **Dynamic range at 1 \mu m**: 2 waves

**Imagine Optic Shack–Hartmann sensor (HASO128)**
- **Area**: $14 \times 14 \text{ mm}^2$
- **Resolution**: $133 \times 133 (114 \mu \text{m})$

A typical setup:
- **Input**
  - Polarizer
  - Faraday rotator
  - $\lambda/2$ mirror
  - Pick-off mirror
- **Output**
  - WFS1
  - NF1
  - Image relay/Spatial filter
  - WFS2
  - NF2
  - Phase plate
- **SLM**

WFS: wavefront sensor
NF: near-field camera
HRABS controls amplitude by introducing high frequency phase and scattering light (carrier method)

Schematic of carrier method

\[ w = 0.5 (w_1 + w_2) \]

\[ A = A_0 \cos [\pi (w_1 - w_2)] \]

The spatial registration error should be less than half the resolution of the measurement system

Staircase beam-shaping simulation with various spatial registration errors (resolution = 142 μm)

- Perfect registration
- Magnification error = 2.3% Translation error = 90 μm
- Rotation error = 21 mrad

Wavefront pattern (W) on SLM
Optimize (Mx, My, x0, y0, θ) for minimum difference between W' and W

Measured wavefront (W') on the sensor

\[
\begin{align*}
x' &= (M_x x - x_0) \cos \theta + (M_y y - y_0) \sin \theta \\
y' &= -(M_x x - x_0) \sin \theta + (M_y y - y_0) \cos \theta
\end{align*}
\]
The influence of energy fluctuation is stabilized by using a spatially disjoint anchoring technique

- The fluctuation in total energy of a laser beam renders the closed-loop operation unstable
  - the algorithm cannot distinguish whether the fluence change was caused by its own control or by energy fluctuation
- A two-step iteration overcomes this problem (assuming no extra energy measurement)
  - two disjoint regions are sequentially used for energy scaling

Illustration of the two-step iteration process used in flat-amplitude shaping
HRABS was installed in a multiterawatt system*

- SLM is installed after OPCPA
  - OPCPA is attenuated to 10% of the full energy

- Two wavefront sensors were installed
  - WFS1: near SLM, WFS2: on the compressor diagnostic table
  - Wavefront sensors provide near-field images as well as wavefront

Peak-to-mode of the OPCPA beam improves from 45% to 20%

Closed-loop with WFS1

- peak-to-mode (p–m) = 45%
- peak-to-mode (p–m) = 20%
- relative rms = 21%
- relative rms = 5%

Peak-to-mode \( \equiv \max \left( \frac{F_{\text{actual}} - F_{\text{mode}}}{F_{\text{mode}}} \right) \)

Relative rms \( \equiv \text{rms of} \left( \frac{F_{\text{actual}} - F_{\text{ideal}}}{F_{\text{ideal}}} \right) \)
OPCPA wavefront is corrected within 0.01 waves rms

- $p-v = 0.6$ waves
- $\text{rms} = 0.09$ waves
- $p-v = 0.066$ waves
- $\text{rms} = 0.007$ waves
Closed-loop with WFS1

Beam shaping converges within 20 iterations

Fluence movie

Wavefront movie

* Fluence and wavefront map at each iteration belongs to the same OPCPA pulse
Wedge aberrations in the system introduce image blurring at WFS2

- A wedge in the imaging system breaks the Abbe sine condition
  - the more the tilt and the wedge angle, the more blurred
- A $3^\circ$ wedge was found and removed for WFS2 imaging
  - there are still unexplained wedges distributed in the system

SLM map is numerically smoothed at each iteration.
Closed-loop with WFS2

Peak-to-mode of the OPCPA beam improves from 40% to 25%

- \( p-m = 40\% \)
- relative rms = 9%
- \( p-m = 25\% \)
- relative rms = 7%

SLM map is smoothed by convolving with a blurring function.
Closed-loop with WFS2

OPCPA wavefront is corrected within 0.04 waves rms

Wavefront (before correction)

Wavefront (after correction)

Lineout comparison

- $p-v = 0.67$ waves
- $rms = 0.16$ waves
- $p-v = 0.19$ waves
- $rms = 0.04$ waves

SLM map is smoothed by using Legendre basis functions.
Laser-damage threshold of the SLM at 5 Hz is $230 \pm 10 \text{ mJ/cm}^2$

- Small-spot damage threshold ranges from 0.6 to 2 J/cm$^2$ indicating defect-limited performance
  - large area damage test is needed
- The damage threshold is determined by slowly ramping up the energy over a large sample area
  - distribution of defects is sparse (about 4 pixels over the whole area)
  - damage does not necessarily occur at the peak fluence
  - three samples (one active, two passive) exhibit the same damage threshold

The SLM sample survived 9 h of irradiation (5 Hz) at an apparent energy density of 230 mJ/cm$^2$.
  - cf. apparent damage fluence is 280 mJ/cm$^2$. 

Sorted fluence curve

- High energy (first damage observed)
- Safe energy

$F_{\text{th}}$: damage threshold

Total area of SLM

Pixel number
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