20kW Short Pulse CO\textsubscript{2} Laser System for LPP Sn EUV Source

K. Nowak, H. Hoshino, T. Suganuma and Akira Endo*

Extreme Ultraviolet Lithography System Development Association
Gigaphoton Inc*

2008 EUVL Workshop
11 June, 2008
Wailea Marriott Hotel, Hawaii

Ver. 1.0

Acknowledgments
This work was supported by the New Energy and Industrial Technology Development Organization -NEDO- Japan.
Outline

- Introduction
  - High Power CO$_2$ Laser development today

- Topics
  - Limitation of power increase of a single beam
  - Thermal distortion of optical components
  - Broad band amplification for higher efficiency

- Summary
High power CO2 laser MOPA system

Laser Power: 13 kW
Pulse Width: 20 ns
Repetition Rate: 100 kHz
Beam quality: M2 1.1
Pulse energy stability: 2% (3s, 500 pulses)

Laser System

- Oscillator
  - Wave length: 10.6um
  - Rep. rate: 100kHz
  - Pulse width: 20 ns (FWHM)

- Pre-Amplifier
  - RF-excited CO2 laser
  - Rep. rate: 100kHz
  - Pulse width: 20 ns (FWHM)

- Main-Amplifier
  - RF-excited CO2 laser

13 kW EUV100 W at I/F equivalent

Laser beam profile
Configuration of Discharge Tubes of Axial Flow CO$_2$ Laser

Second floor of the tubes is not shown

Gain area
Laser Beam Delivery in Cascade Amplifiers

Filling Factor

\[
\text{Filling Factor} = \frac{\text{Laser beam cross section}}{\text{Gain cross section}}
\]

Measurement and analysis of beam delivery

Fine matching

Beam delivery distance
Extraction Efficiency of Amplifier

- Pulse extraction efficiency increase vs filling factor

Pulse amplification efficiency = pulse output power (out - in) / CW output power
Amplification model of RF-excited CO₂ laser

**Frantz - Nodvik Equation**

\[
E_{\text{out}} = E_s \cdot \ln[(1 + \exp(g_0 \cdot L)[\exp\left(\frac{E_{\text{in}}}{E_s}\right) - 1]]
\]

- \(E_{\text{in}}\): input fluence [J/cm²]
- \(E_{\text{out}}\): output fluence [J/cm²]
- \(g_0\): gain [%/cm]
- \(E_s\): saturation fluence [J/cm²]
- \(L\): gain length [cm]

Experimental result of Extracted Power with Single-Line Oscillator and 15 kW amplifier module at 100 kHz

-\(\Diamond\) - is the extracted power of amplification result.

Extracted power estimation is over 5 kW.

Extracted efficiency is over 5.5% from pumping power.
Average power increase in the last two years

<table>
<thead>
<tr>
<th>Date</th>
<th>Laser Power [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>’06 Feb.</td>
<td>2</td>
</tr>
<tr>
<td>’06 Oct.</td>
<td>2</td>
</tr>
<tr>
<td>’06 Dec.</td>
<td>6</td>
</tr>
<tr>
<td>’07 Feb.</td>
<td>6</td>
</tr>
<tr>
<td>’07 Oct.</td>
<td>10</td>
</tr>
<tr>
<td>Now ’08 May</td>
<td>14</td>
</tr>
</tbody>
</table>
Power limitation

Present:
- 60W MO power
- 3kW output

Optimum:
- 6.4kW MO power
- 12.3kW output

(ZnSe)
- Moderate thermal lensing
- Minor mirror distortion

(Diamond)
- Severe thermal lensing
- Significant mirror distortion

Extraction efficiency

Oscillator power [W]

5kW amp
15kW amp
Total system

Pulsed Optical Damage (1J cm$^2$)
Thermal loading of optical components – an illustration

![Graph showing beam diameter and power over distance with labels for Expander (ZnSe), In. Window (ZnSe), and Out. Window (ZnSe).]

- MO power: 60W
- 100kHz, 20ns
- Duty factor: 0.10
- Amps off 0.10 duty
Application to FAF amp chain link

- Each correction loop is autonomous – simplicity
- Master control necessary
Stabilization of beam delivery

![Graph showing beam diameter over time with and without AO control]
Output laser beam characteristics

Output laser beam pulse/quality

Temporal pulse shape

Beam quality

Pulse duration: 20 ns (FWHM)
Pedestal component: <10%

Beam quality: M2=1.1
No significant change after amplification.

Laser beam profile
Long time operation

1hr non-stop operation of 100kHz CO2 laser, 13kW, 10% duty cycle

On: 1.6 ms
Off: 14.4 ms
Vibrational-Rotational CO$_2$-N$_2$ Laser Energy Level Diagram

- CO$_2$ molecular vibrational mode
  - Symmetric stretch mode ($v_1$)
  - Bending mode ($v_2$)
  - Asymmetric stretch mode ($v_3$)
- N$_2$ Molecule

Energy Levels:
- (000)
- (001)
- Rotation Level $J=19$
- Rotation Level $J=20$
- Excitation

Rotation Level Relaxation Time: 1-2 ns

Vibration energy transfer during collision ($\Delta E=2.2x10^{-3}[\text{eV}]$)

10-30% of N$_2^*$
Rotational Gain Bandwidth

< Pressure Broadening >

\[ \Delta \nu = 7.58(\Phi_{\text{CO}_2} + 0.73\Phi_{\text{N}_2} + 0.64\Phi_{\text{He}}) \times P(300/T)^{1/2} \]

\( \Phi \): partial ratio

\( P \): Pressure [torr]

\( T \): Temperature [K]

Typical Gas Parameter

- \( \text{CO}_2 \):N\(_2\):He=1:1:8
- Pressure: 100 [torr]
- Temperature: 450 [K]

\[ \Delta \nu = 424 \text{ [MHz]} \]

⇒ Estimate pulse duration

from the Fourier transform limit of a Gaussian pulse

\[ \Delta \nu \cdot \Delta t = 0.44 \]

⇒ \( \Delta t \sim 1 \text{ ns} \)

Short pulse Amplification is limited of 1ns
Relaxation time (RF-excited CO\textsubscript{2} laser)

**Oscillator Parameter**
- Pulse to Pulse interval: \(10 \mu s\) (100kHz)
- Pulse duration: \(10\) ns

**Vibrational relaxation time**
\[ \tau_v = 0.5 \mu s \quad \text{Pressure: 100 [torr]} \]

**Rotational relaxation time**

\[ \tau_r = \left[ 7.58(\phi_{CO_2} + 0.73 \cdot \phi_{N_2} + 0.64 \cdot \phi_{He}) \cdot P \cdot \sqrt{\frac{300}{T}} \cdot 10^6 \right]^{-1} \]

\(\Phi\): partial ratio
\(P\): Pressure [torr]
\(T\): Temperature [K]

Typical Gas Parameter
- \(CO_2:N_2:He=1:1:8\)
- Pressure: 100 [torr]
- Temperature: 450 [K]

\[ \tau_r = 2.3\text{ ns} \]

⇒**Gain of short pulse amplification is decreased than CW amplification**
Theoretical predictions about multi-line operation:
• Most effective for pulses of duration smaller or comparable to rotational relaxation times of the medium
• Up to 20% more extraction with 4 CO2 lines at 15ns pulses
  For pulses >50ns multi-line not significant
• Current approach – solid-state broadband seeder and regenerative amplification in CO2 medium
Efficient amplification

Numerical Calculation Result of Amplification with Multi-Line Oscillator

This work was performed by Research Institute for Laser Physics, St. Petersburg, Russia [V.E. Sherstobitov]

Estimated extracted power of 15 kW amplifier module in case of input power with 3 kW

- Multi-line: > 6.5 kW (5 kW × 1.3)
- Single-line: > 5 kW

Extracted efficiency from pumping power is estimated

- Multi-line: > 7.2 %
- Single-line: > 5.5 %

-X- is the amplification ratio between the (P16-P22) spectrum and the P20 line
20 kW Short Pulse CO$_2$ laser MOPA system

Single beam, 20 kW CO$_2$ laser system in sight

- **Power Limitation**
  - *Damage of Optics*
    - Diamond window
  - *Filling Factor*
    - Compensation of beam diffraction and thermal lensing
  - *Saturation*
    - Broadband amplification

AMP1
RF-excited CO$_2$ laser
Pumping : 50 kW

AMP2
RF-excited CO$_2$ laser
Pumping power : 120 kW

AMP3
RF-excited CO$_2$ laser
Pumping power : 120 kW

Multi-line Oscillator
Rep. rate : 100kHz
pulse width : 20 ns (FWHM)

20 kW
(200mJ at 100kHz)
High Power CO$_2$ laser MOPA system has been achieved with:

- 13 kW output power at 100 kHz, 20 ns (FWHM)
- duty: 10% (on 10msec, off 90msec)

Efficient amplification with RF-excited CO$_2$ laser

- Extraction efficiency of short pulse amplification is 30% to the case of CW oscillation
- From numerical model, efficiency of Multi-line amplification is 1.3 higher than Single-line

Single beam, 20kW short pulse CO$_2$ laser system is soon available