# Development of the reliable 20 kW class pulsed carbon dioxide laser system for LPP EUV light source

Junichi Fujimoto, Takeshi Ohta*, Krzysztof M. Nowak*, Takashi Suganuma*,
Hidenobu Kameda*, Masato Moriya*, Toshio Yokoduka*, Koji Fujitaka*,
Akira Sumitani** and Hakaru Mizoguchi

Gigaphoton Inc.; 400 Yokokura-shinden Oyama-shi Tochigi-ken 323-8558, JAPAN
*KOMATSU Ltd.; 400 Yokokura-shinden Oyama-shi Tochigi-ken 323-8558, JAPAN
**KOMATSU Ltd./EUVA; 3-25-1 Shinomiya Hiratsuka-shi Kanagawa-ken 254-0014, JAPAN

## ABSTRACT

Laser Produced Plasma (LPP) Extreme Ultra Violet (EUV) light source is expected to be used for next generation lithography. To realize such performance for industrial use, the main driver laser is one of the key components. Our source uses a high power pulsed carbon dioxide ($CO_2$) laser as a plasma driver. A master oscillator and a power amplifier (MOPA) system based on a new configuration of an RF-excited $CO_2$ laser is the key to high efficiency. This pulsed $CO_2$ laser system has started to operate. This report shows its initial performance. Also for a reliable industrial system, the optical instability caused by vibration and thermal distortion of optics should be suppressed at 20 kW output level. The primary design of key modules, such as mirrors, for the $CO_2$ laser, and dynamic design concepts are shown in this report. We have achieved 7.6 kW, 14 nsec, 100 kHz pulsed output in this configuration.

**Keywords:** Extreme Ultra Violet light source, EUV, Laser Produced Plasma, LPP, pulsed $CO_2$ laser, Lithography, MOPA

## 1. INTRODUCTION

EUV light source is expected to be used for next generation lithography. For the past several years, the source has been one of the most critical issues. In addition, especially an LPP type EUV light source system is expected to provide higher output power (>200 W) in order for the scanners to obtain higher throughput. To realize such performances as higher power and high reliability required for industrial use, the main driver laser is one of the key components [1][2][3]. Our

e-mail address: junichi_fujimoto@gigaphoton.com

LPP type EUV light source system uses a high power pulsed $CO_2$ laser as the main driver laser. Our approach is a MOPA system based on a small average-power pulsed master oscillator and a chain of some power amplifiers [4][5]. The EUV light source system for microlithography is required of the intermittent pulsed operational mode and the stable pulsed beam performance. There is no such system available yet at 20 kW power level. Also, the thermal management and the dynamic stabilities are very important factors to realize the mass-production level reliable laser output, since the total length of this laser beam path is longer than 50 meters and the number of optics in the main beam path exceeds 100. To operate this type of laser at mass-production level, there are two critical issues that need to be addressed. One is the stability of the optical elements. The system operates in a burst mode, such as 1000 msec ON and 500 msec OFF for die exposure, and also several second OFF for cassette change.

In this paper, we will describe the system design and the operational performance of the MOPA laser system developed as the driver laser for the LPP type EUV light source used in a mass-production line. In the description to follow, the requirements for the LPP type EUV light source and the driver laser are described in Section 2. In Section 3, the system configuration and the function of each module are shown. The result of this study is shown in Section 4. The fundamental input/output characteristics of each module and the initial system performance are shown. Further, the design concepts of major laser components are described.

## 2. REQUIREMENT for EUV

First, we would like to review the requirements of a $CO_2$ laser as an industrial LPP type EUV light source. Higher efficiency and operational reliability of the system are key for industrial use. Figure 1 shows the typical setup of the EUV light source system. To minimize optical loss of EUV, the EUV generation vessel is located closely beside the scanners. To minimize footprint in a clean room, the $CO_2$ laser system is located on a different floor (usually downstairs) from where the scanner is located. These two places have different vibration design specifications. Usually, the floor where the $CO_2$ laser is installed is less stiff than where the scanner is located. Table 1 shows the major requirements of EUV light source system and the driver laser.

| | units | Specifications |
|---|---|---|
| EUV power (13.5 nm) | W | 200 |
| EUV power stability 3σ | % | 12.0 |
| Conversion Efficiency | % | 5.0 |
| $CO_2$ power (10.6 μm) | kW | 20 |
| $CO_2$ laser pulse duration | nsec | 15 – 20 |
| $CO_2$ laser energy stability 3σ | % | 6.0 |

►CE: conversion efficiency from $CO_2$ laser to EUV light

Table 1. Major target specifications of EUV and $CO_2$ Laser

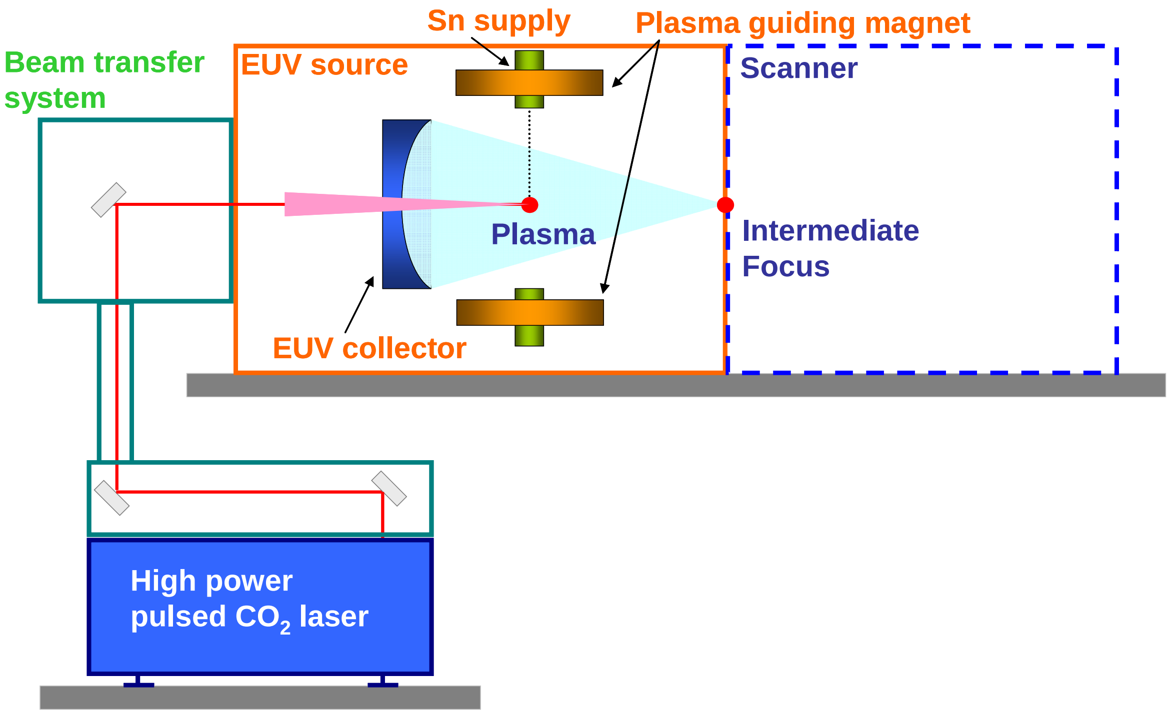

Figure 1. LPP EUV light source System

## 3. SYSTEM CONFIGURTION

### 3-1 **Laser components**

Our driver laser is configured of a MOPA system based on a small average-power pulsed master oscillator and a chain of some power amplifiers. Figure 2 shows the configuration of a $CO_2$ laser system. This system contains three major modules.

The targeted specifications of this laser system are described below. The Oscillator (OSC) generates pulses at the repetition rate of 100 kHz, with 20 nsec pulse duration, and with 150 W (1.5 mJ, 100 kHz) power. The OSC contains two major parts. One is master-OSC that oscillates a pulse, and the other is OSC-AMP that amplifies the pulse energy. The pre-amplifier (pre-AMP) amplifies the pulse from 150 W to 3 kW (30 mJ, 100 kHz) output level with the slab-type discharge chamber. The main-amplifiers (main-AMP) further amplify the pulse from 3 kW to 20 kW (200 mJ, 100 kHz) output level with the two sets of fast gasflow-tube-type discharge systems. This system has has laser beam path that is approximately 100 m long. To maintain the laser performance, the laser alignment needs to be maintained within +/- 200 micro-radian level and within +/- 250 µm level in terms of its position. The laser goes out of alignment mainly due to the vibration propagated from the floor and the thermal deformation of optics caused as the laser power is absorbed in and on the mirrors, which causes the beam direction to fluctuate.

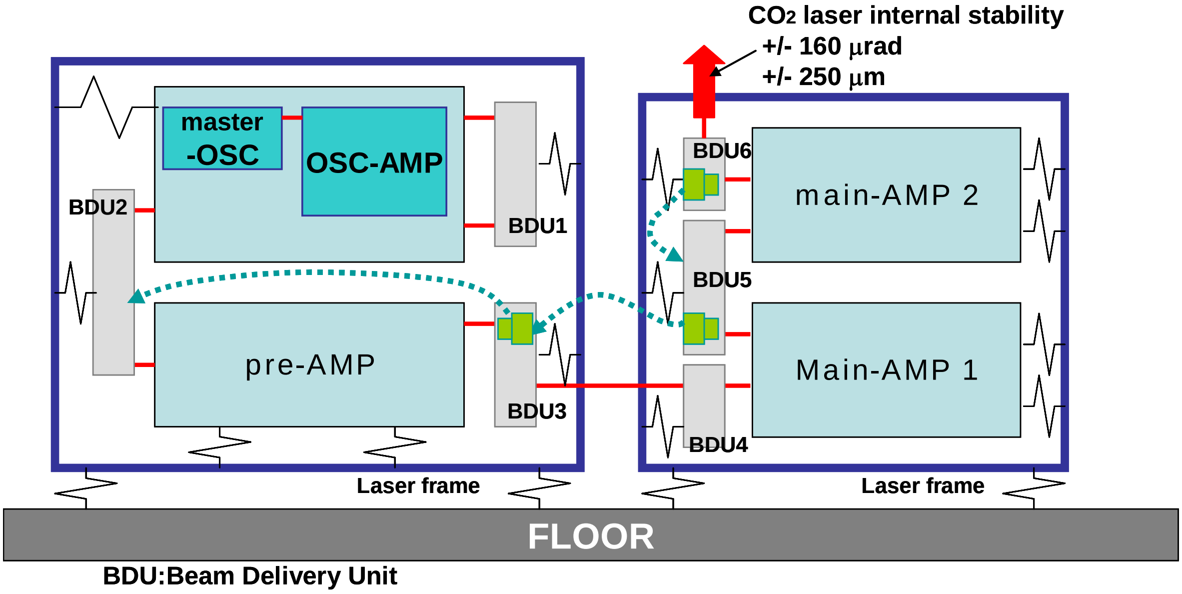

Figure 2. $CO_2$ laser system configuration

### 3-2 Beam Delivery Unit

This system has several Beam Delivery Units (BDUs) which correct the beam direction and the beam deformation caused by floor vibration and thermal distortion of optics. Our system has several types of BDUs, which are described in Table 2.

| | for Dynamics | | for Thermal Adaptive Optics |
|---|---|---|---|
| | position | pointing | |
| BDU 1-4 | none | none | none |
| BDU 2-3 | none | none | control |
| BDU 3-5 | control | control | control |
| BDU 5-6 | none | none | control |

Table 2. BDU modules function

## 4. RESULTS

4.1 Laser performance

Figures 3, 4, 5 and 6 show the main performance of the master-OSC, OSC-AMP, pre-AMP, and main-AMP modules respectively. The OSC has constant pulse energy 150 μJ up to 100 kHz in Figure 3. Also the beam profile is stable at 100 kHz, 15W power level.

The OSC-AMP amplifies the pulse from 10 W (100 μJ, 100 kHz) to 100 W (1 mJ, 100 kHz, target 150 W) and inputs the pulse to the pre-AMP. The results are shown in Figure 4. The performance of the output v.s. RF duty of 100% at 4 kW with 6 W input, the beam profile, and the pulse duration are also shown.

The pre-AMP amplifies the pulse from 100W to 1.7 kW (target 3 kW) and inputs the pulse to the main-AMP. The results are shown in Figure 5. The performance of the input and output characteristics at RF duty of 85% at 80 kW, output power v.s. RF duty at input of 100W, the beam profile, and the pulse duration are also shown.

The main-AMP amplifies the pulse from 1.7 kW (17 mJ, 100 kHz) to 7.6 kW (76 mJ 100 kHz, target 20 kW) and inputs the pulse to the EUV vessel. The results are shown in Figure 6. The performance of the input and output characteristics at RF duty of 80% at 200 kW, output power at input of 1.7 kW, the beam profile, and the pulse duration are also shown.

Each module shows the performance at feasible level to meet the system specifications. The master-OSC, the OSC-AMP, the pre-AMP, and the main-AMP are going to be tuned for meeting the targeted specifications.

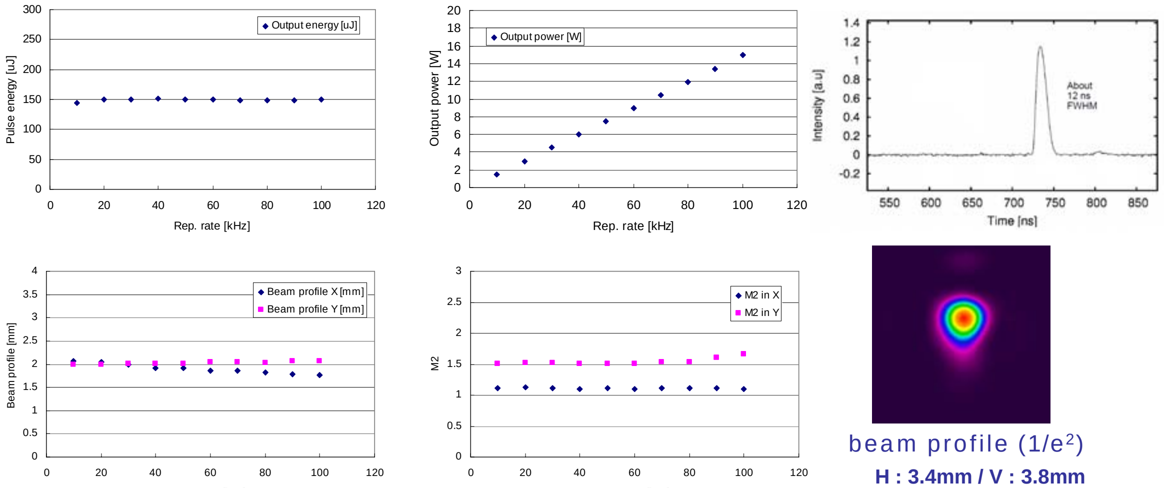

Figure 3. master-OSC output performance

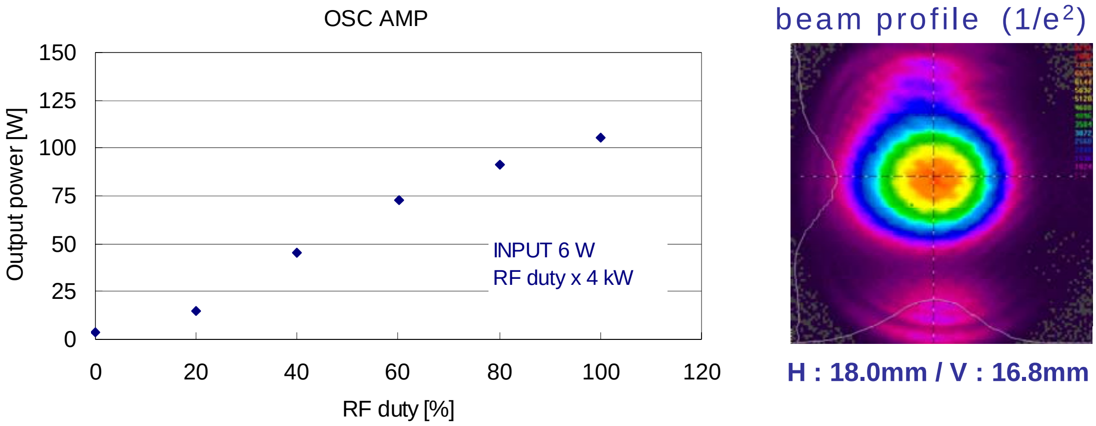

Figure 4. OSC-AMP output performance

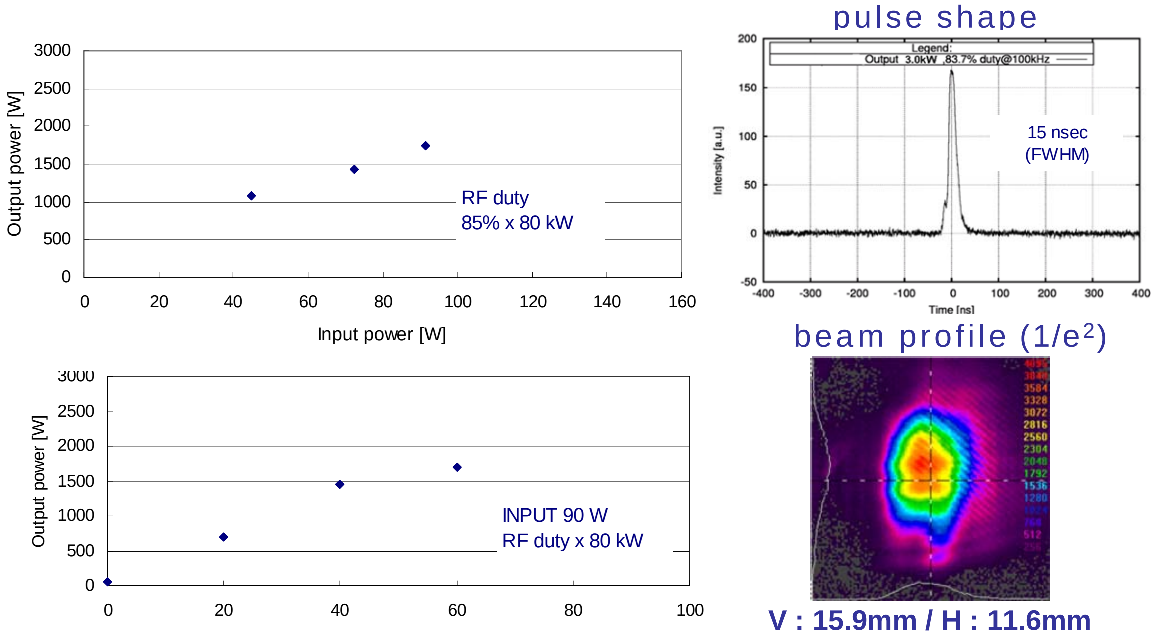

Figure 5. pre-AMP output performance

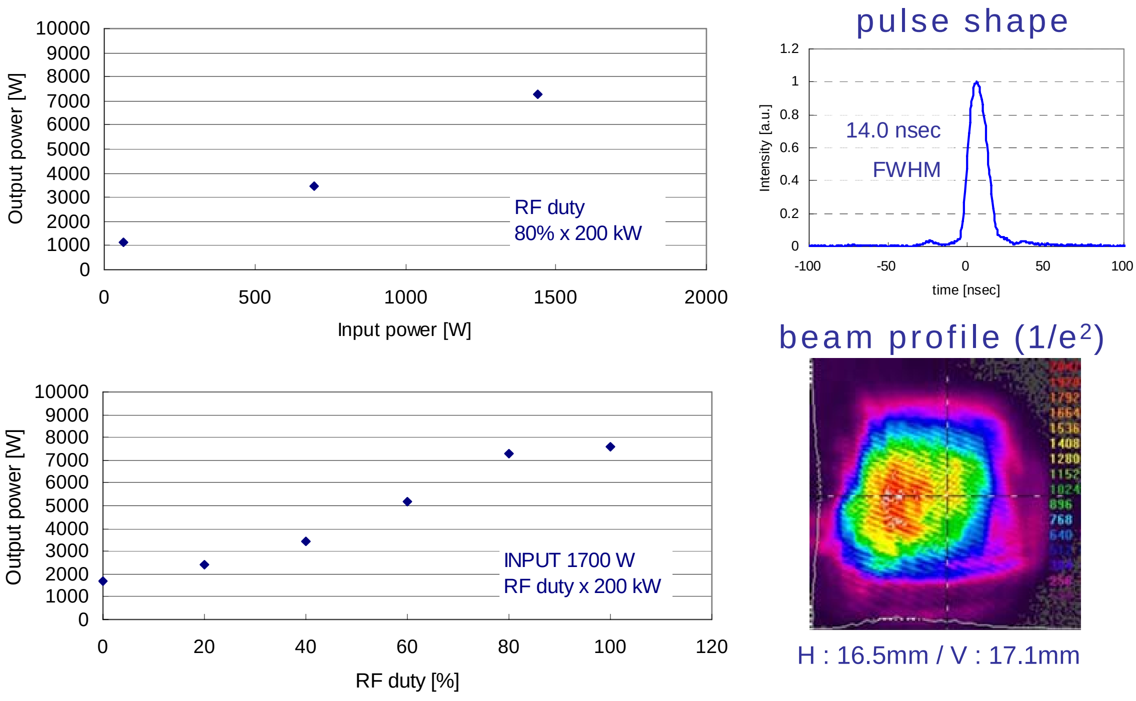

Figure 6. main-AMP output performance

## 4.2 Dynamics stabilities

For industrial use, laser alignment also should be protected from the vibration which mainly propagates from the floor. For this purpose, there are two main issues that need to be taken care of. One is the mechanical stiffness of optical construction, and the other is the fast (>100 Hz) feedback system for the correction of the alignment.

Figure 7 shows the schematics of dynamic design of the optical components. The installation floor for a laser frame needs to have greater stiffness of more than 5 to 10 Hz. The laser frame to the main module (e.g., OSC, pre-AMP, and main-AMP) needs more than 15 to 20 Hz stiffness. And the main module to each optical element (e.g., optics holder, optics, and sensor) needs more than 100 Hz stiffness. This system is designed to meet these design specifications. And the fast feedback alignment correction system will be equipped in BDU5-6.

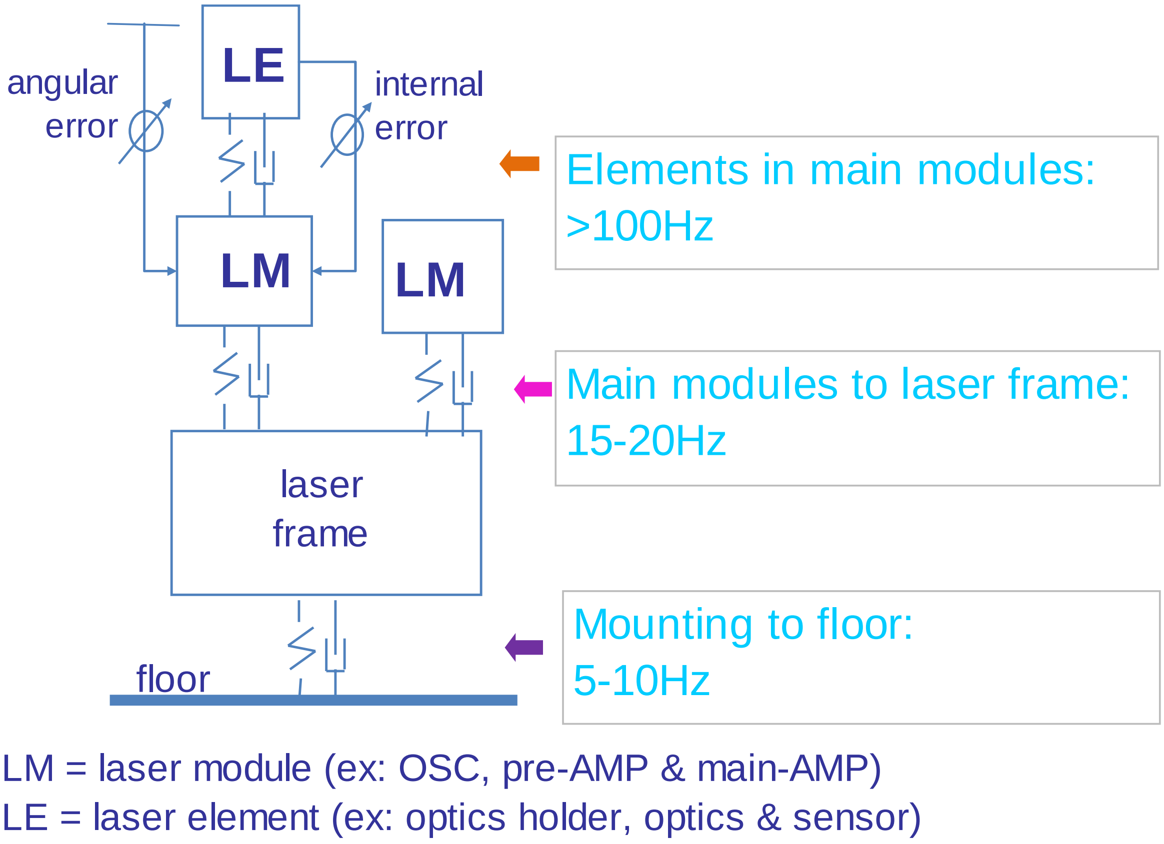

Figure 7. Dynamic stiffness of laser components

## 4.3 Thermal stabilities

Thermal distortion of optical components causes the beam profile to deform and the beam to go out of alignment. When the reflective mirrors and the window receive a heat load from the $CO_2$ laser beam at their coating and base materials, the optics deforms and the diffractive index of the material change. Deformation of the mirror surfaces result in the distortion of the beam profile. The window design will be reported later.

We have taken two actions for solving the thermal influence on the mirror.

1. Improvement of material --- lower thermal expansion, higher thermal conductivity
2. Improvement of cooling structure --- the symmetrically shaped cooling channel for uniform distortion

Figure 8 shows the simulation results of the distortion of the mirror surfaces with various design conditions. The input beam of the $CO_2$ laser is the Gaussian profile beam with 40 kW (= 80 w; 0.2% surface absorption safety factor 2.3). The standard, commercially available mirror for a CW $CO_2$ laser is mainly made of copper ("Cu current" in figure). The cooling channels behind the mirror surface are not symmetric with respect to its center. We have designed the symmetrically shaped water cooling channel to improve symmetrical cooling property ("Cu improved" in figure). To reduce the surface distortion, we have designed with lower surface expansion material, which is silicon carbide ("SiC improved" in figure). According to the calculation results, 80% improvement has been obtained by improving the water channel. 61% improvement has been obtained by changing the material. These mirrors with the improved design are going to be applied in our system.

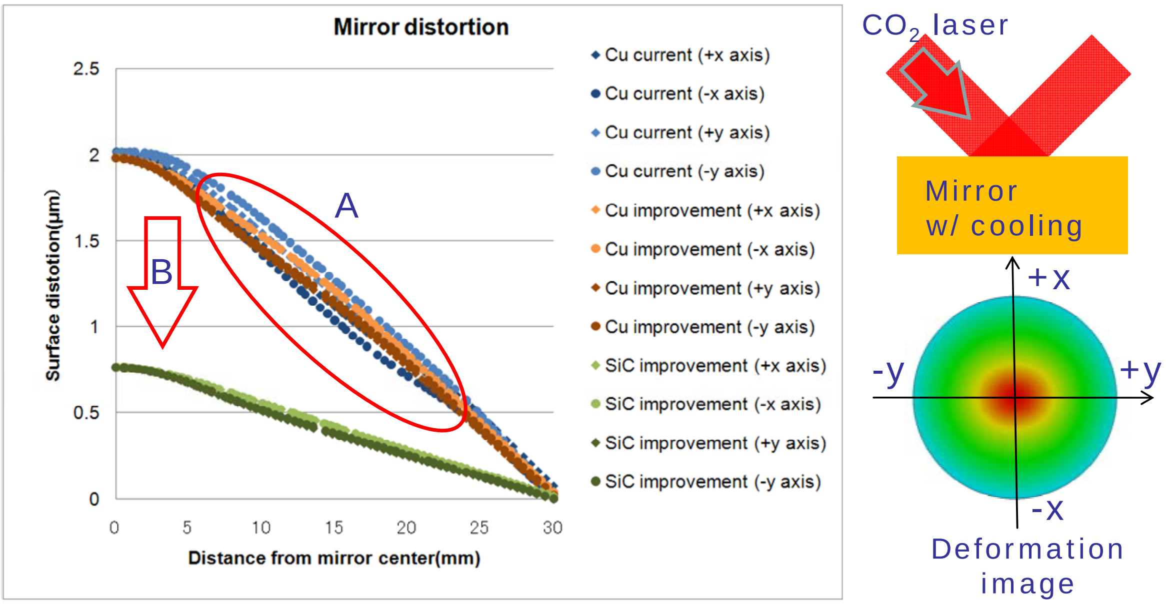

Figure 8. Comparison of thermal distortion of mirrors with different design by simulation

## 5. CONCLUSION

The main performance of the $CO_2$ laser in this study and the target are shown in Table 3. In this initial experiment, these performances suggest that the targeted specifications for the driver laser for EUV light source are achievable. We have obtained the fundamental performance results of the key modules. Our system with the MOPA configuration shows basic performance to achieve the final target. Also there are still more room for improvement to get higher power. For the next step, we are going to employ the new optics that we have described in this paper and the active compensation feedback control device in our system for longer and reliable operation. Also the Sn target will be adopted to obtain EUV light performance. We believe the stable performance of the driver laser is one of the key requirements to achieve reliable EUV light source for industrial use.

To obtain higher throughput in wafer fabrication, more EUV power will be required for the years to come. That means that higher $CO_2$ laser power is also required shortly. We need to improve each element to obtain more stable and higher laser power.

| | units | Final Target | Current results |
|---|---|---|---|
| Output power | kW | 20 | 7.6 |
| Rep. rate | kHz | 100 | 100 |
| Pulse energy | mJ | 20 | 7.6 |
| Beam profile ($1/e^2$) | $mm^2$ | 18 dia. | 16.5 × 17.1 |

Table 3. $CO_2$ performance summary

## 6. ACKNOWLEDGEMENTS

We would like to thank Akira Endo for many inputs and suggestions.

Also many thanks to the co-workers of the EUV development team in Research Center Komatsu Ltd. and the development team in Gigaphoton Inc.

A part of this work was supported by the New Energy and Industrial Technology Development Organization (NEDO) in JAPAN.

## 7. REFERRENCE

[1] Hakaru Mizoguchi, Tamotsu Abe, Yukio Watanabe, Takanobu Ishihara, Takeshi Ohta, Tukasa Hori, Akihiko Kurosu, Hiroshi Komori, Kouji Kakizaki, Akira Sumitani, Osamu Wakabayashi, Hiroaki Nakarai, Junichi Fujimoto, Akira Endo, “1st Generation Laser-Produced Plasma source system for HVM EUV lithography,” Proc. SPIE Vol.7636-07, 763606 (2010).

[2] David C. Brandt, Igor V. Fomenkov, Alex I. Ershov, William N. Partlo, David W. Myers, Richard L. Sandstrom,

Norbert R. Böwering, Georgiy O. Vaschenko, Olch V. Khodykin, Alexander N. Bykanov, Shailendra N. Srivastava, Imtiaz Ahmad, Chirg Rajyaguru, Daniel J. Golich, Silvia De Dea, Richard R. Hou, Kevin M. O'Brien, Wayne J. Dunstan, "LPP Source System Developmet for HVM," Proc. SPIE Vol. 7636-53, 76361I (2010).

[3] Hakaru Mizoguchi, Tamotsu Abe, Yukio Watanabe, Takanobu Ishihara, Takeshi Ohta, Tukasa Hori, Akihiko Kurosu, Hiroshi Komori, Kouji Kakizaki, Akira Sumitani, Osamu Wakabayashi, Hiroaki Nakarai, Junichi Fujimoto, Akira Endo, "1st Generation Laser-Produced Plasma 100W Source System for HVM EUV Lithography," EUVL Symposium 2010 International Symposium on Extreme Ultraviolet Lithography SO-03 (2010).

[4] Krzysztof M. Nowak, Takashi Suganuma, Toshio Yokotsuka, Koji Fujitaka, Masato Moriya, Takeshi Ohta, Akihiko Kurosu, Akira Sumitani, Junichi Fujimoto, "Improving Efficiency of MOPA Laser System for LPP EUV Source," 2010 International Workshop on EUV Lithography, Source-1 (2010).

[5] Takeshi Ohta, Krzysztof Nowak, Takashi Suganuma, Toshio Yokotsuka, Kouji Fujitaka, Masato Moriya, Akihiko Kurosu, Akira Sumitani, Junichi Fujimoto, Hakaru Mizoguchi, "Improving efficiency of pulsed $CO_2$ laser system for LPP EUV light source," EUVL Symposium 2010 International Symposium on Extreme Ultraviolet Lithography, SO-P03 (2010).