Development of the reliable high power pulsed carbon dioxide laser system for LPP EUV light source

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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. And multiline amplification of CO_2 laser is efficient to increase the extraction efficiency in the case of short pulse amplification like this amplification. Numerical result shows the amplification enhancement as 1.3 times higher than the single line amplification. This report shows its initial performance. Multiline configuration is applied to the master oscillator and the efficiency of multiline amplification is verified in our experimental amplifier system. We have achieved 10% energy extraction improvement using 2 lines (P20+P22) as compared to single line (P20).

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 LPP type EUV light source system uses a high power pulsed CO_2 laser as the main driver laser. Our CO_2 laser system is a MOPA system based on a small average-power pulsed master oscillator and a chain of some power amplifiers [4][5][6]. 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. The current MOPA system cannot provide more than 25% overall operation efficiency. The main reason is an insufficient power level at initial amplifier stages. The key to high efficiency is a master oscillator system and a pre-amplifier system based on a novel configuration of a RF-excited CO_2 laser. And multiline amplification is efficient to increase the extraction efficiency in the case of short pulse amplification like this application. Numerical result shows the amplification enhancement as 1.3 times higher than the single amplification.

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 route to increase efficiency are shown. The result of this study is shown in Section 4. Multiline configuration is applied to the master oscillator and the efficiency of multiline amplification is verified in our experimental amplifier system. The fundamental input/output characteristics of each module and the initial system performance are shown.

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. 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

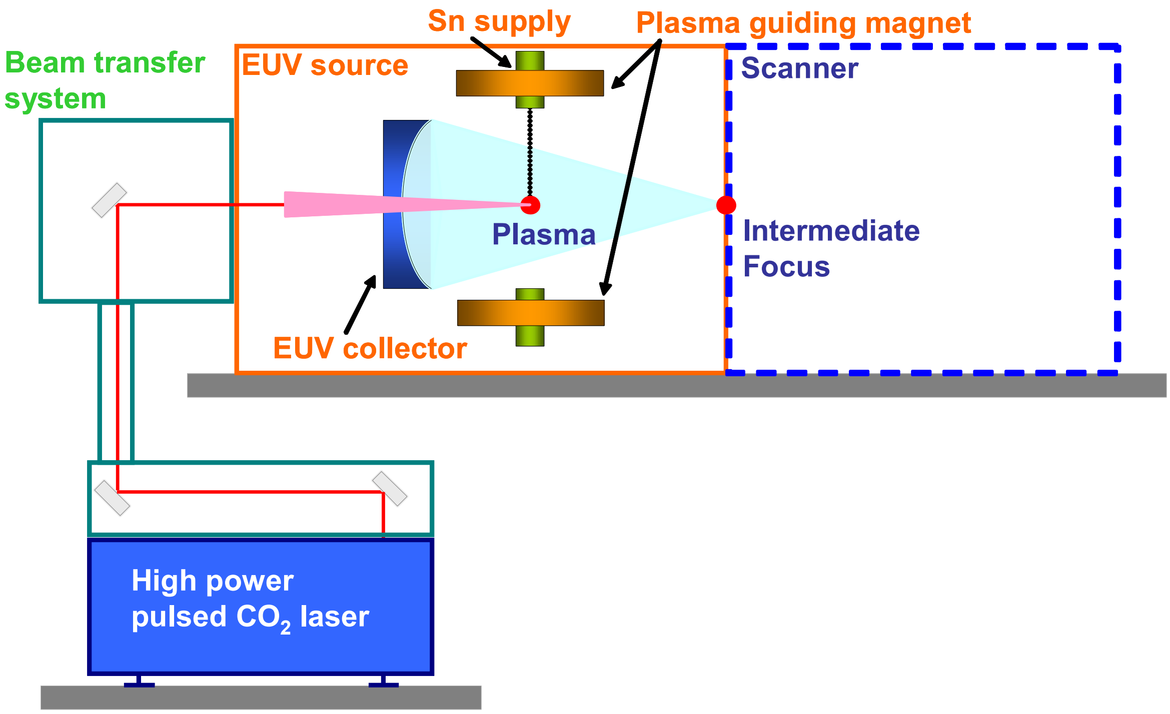


Figure 1. LPP EUV light source System

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 axis gas-flow-tube-type discharge systems.

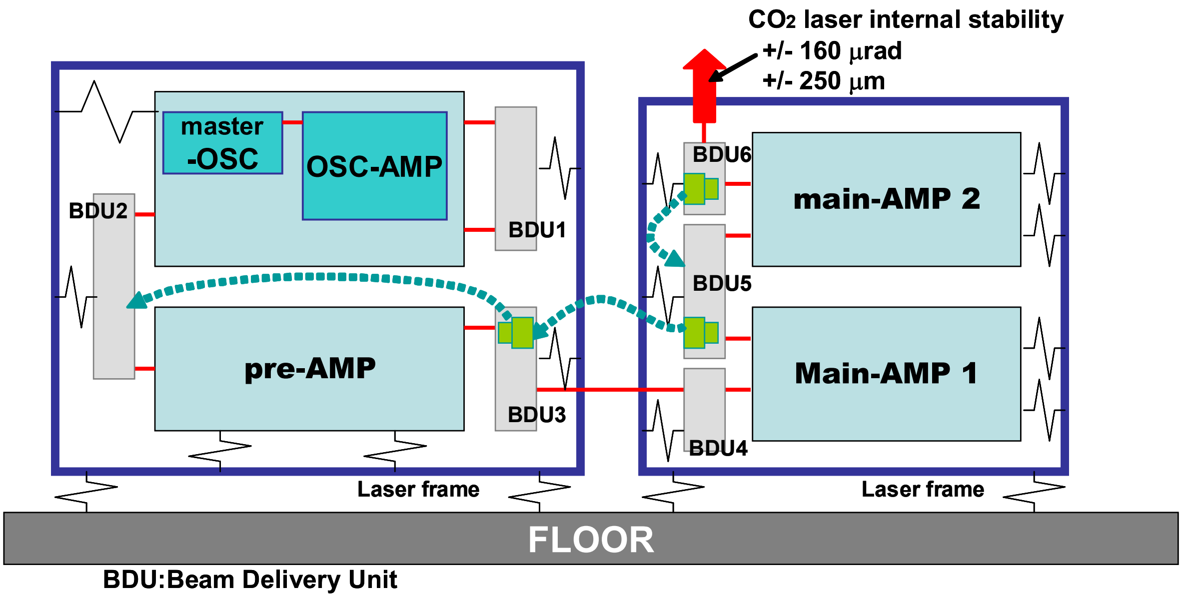


Figure 2. CO_2 laser system configuration

3-2 Efficient pulsed amplification of ns CO_2 laser

Routes to increase efficiency of short pulsed MOPA CO_2 laser system are bandwidth-matched input signal and to maximize signal-medium interaction time and rate. Key aspects to achieve high efficiency are Master Oscillator and Pre-amplifier arrangement.

Master Oscillator consists of a seed laser and CO_2 laser oscillator (Figure 3). The seed laser provides multiple laser transitions of the gain medium simultaneously that match the bandwidth of laser gain line for maximum interaction cross-section. Quantum cascade lasers (QCL) are used to seed the CO_2 laser oscillator with discrete spectrum. QCL can be accurately tuned to particular gain lines of the CO_2 medium with sufficient accuracy. Figure 4 shows the calculation result of multiline amplification. Numerical result shows the amplification enhancement with 4 lines (P16, 18, 20, 22) as 1.3 times higher than the single line (P20) amplification.

Multi-pass amplifier arrangement for Pre-amplifier is the key to maximize signal-medium interaction time and rate. Slab-waveguide amplifier based on RF-discharge excited diffusion-cooled CO_2 laser is effective for this purpose. Figure 5 shows the calculation result of slab-waveguide amplifier. Maximum extraction efficiency is 35-60% from 1-3kW input. This shows the multi-pass amplifier arrangement is highly effective as pre-amplifier.

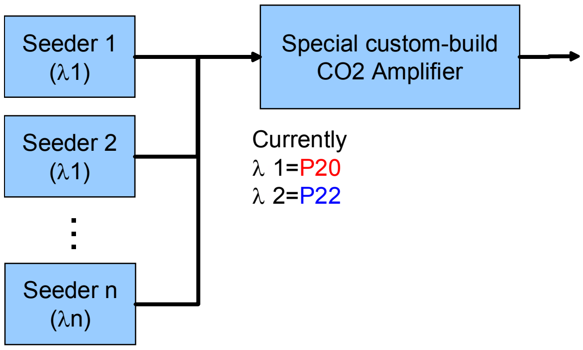


Figure 3. Multi-line master-OSC

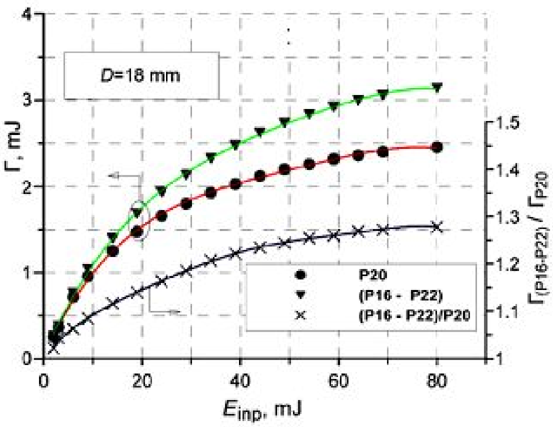


Figure 4. Numerical Calculation Result

of Amplification with Multi-Line Oscillator

(This work performed by Research Institute for Laser Physics,

St. Petersburg, Russia [V.E. Sherstobitov])

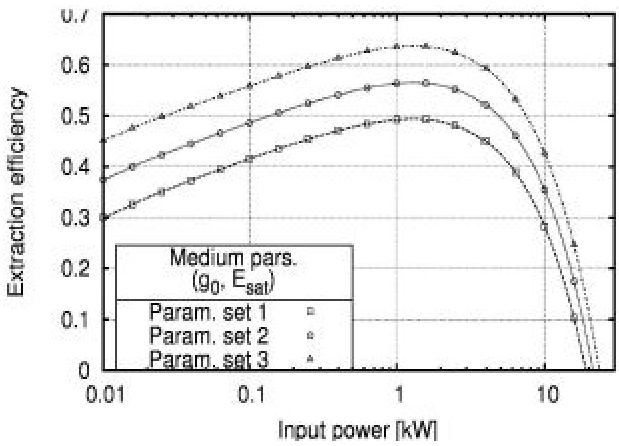


Figure 5. Prediction of pulsed performance of

multi-pass slab amplifier, 20ns, 100kHz

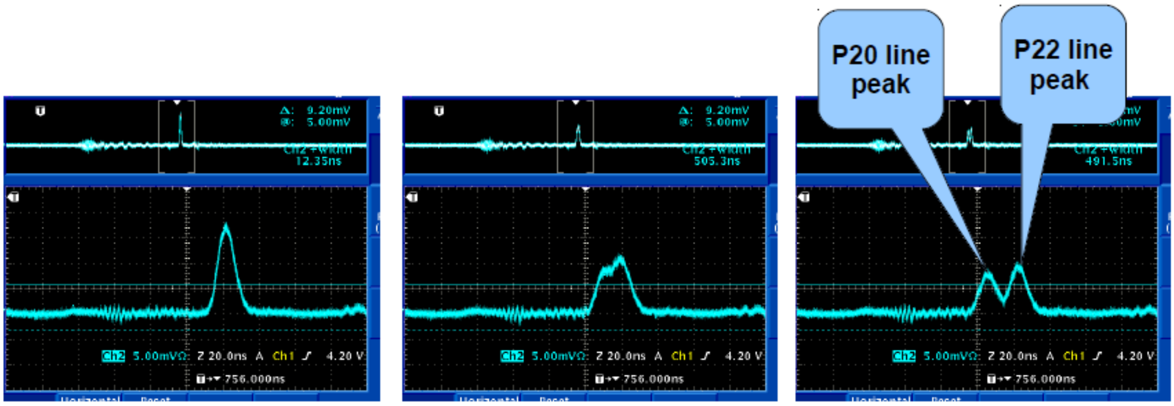
4. RESULTS

4.1 Multi-line oscillator

Figure 6 shows the experimental confirmation result of multi-line output using the multi-line master oscillator. Multi-line seeding and amplification is confirmed by switching individual seeders on and off. Figure 7 shows the performance of pulse width tunability by controlling relative time offset of seeding pulses. In this experiment, the output power is 10.5W at 100kHz.

(a)Seeding at P20 only (b) Seeding at P22 only (c) Seeding at both P20 and P22

Figure 6. Experimental confirmation result of multi-line seeding and amplification



(a)0ns relative offset (13ns FWHM) (b)10ns relative offset (20ns FWHM) (c)15ns relative offset (25ns FWHM)

Figure 7. Pulse width tunability of multi-line master oscillator

4.2 Multi-line amplification

Figure 8 and 9 show the experimental results of multi-line amplification using the multi-line master oscillator and the OSC-AMP. The OSC-AMP amplifies the pulse from 10 W (100 μJ, 100 kHz) to 100 W level (1 mJ, 100 kHz, target 150 W) and inputs the pulse to the pre-AMP. 200W output power was achieved with two lines (P20 + P22) and 10% energy extraction improvement using 2 lines (P20+P22) as compared to single line (P20) was confirmed. Where, extraction efficiency shown in figure 9 is the relative performance of the amplifier with pulsed input as compared to a laser output before conversion into an amplifier operated at the same RF duty level. Also, the result of the pre-AMP with multi-line amplification is shown in Figure 10.

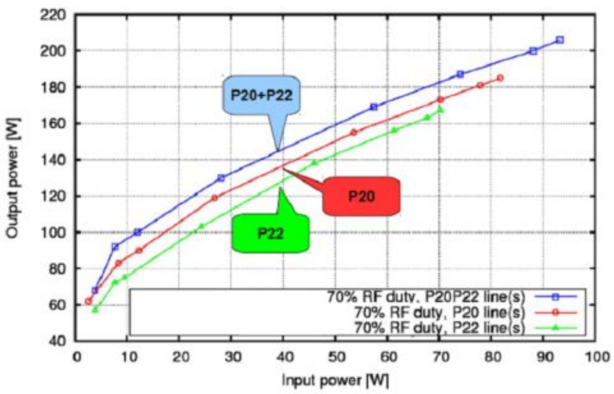


Figure 8. OSC-AMP output performance

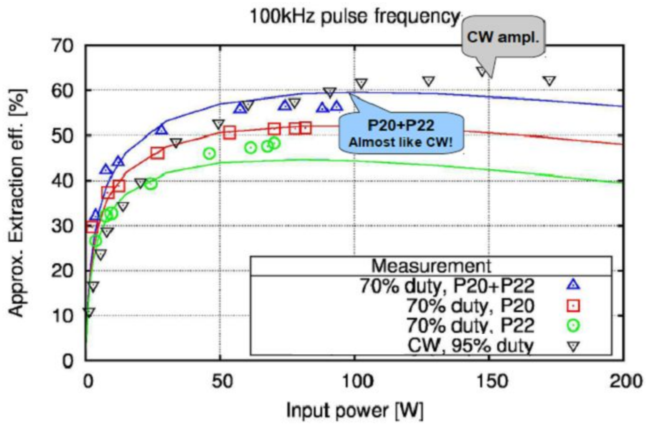


Figure 9. Extraction efficiency of OSC-AMP

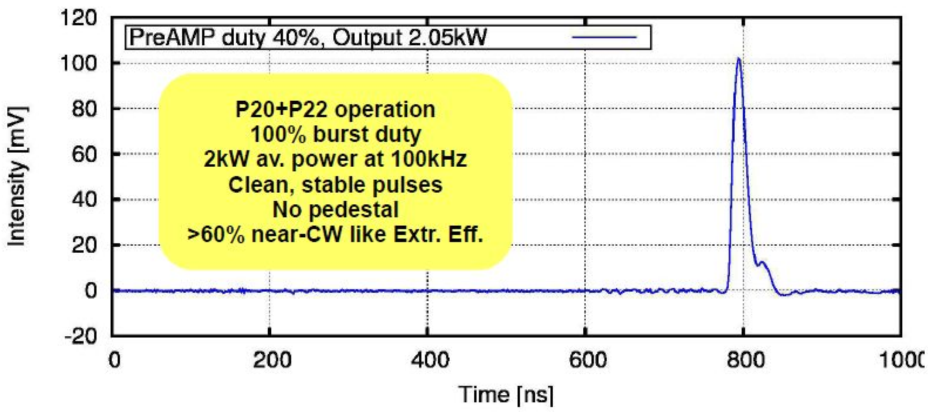


Figure 10. Pre-AMP output performance with multi-line

5. CONCLUSION

A multi-line oscillator was designed and developed (10-20W output). In this initial experiment, multi-line operation (currently P20+P22, more planned soon) was confirmed and 10% energy extraction improvement using 2 lines (P20+P22) as compared to single line (P20) was confirmed. These performances suggest that the targeted specifications for the driver laser for EUV light source are achievable. We have obtained the fundamental performance results for high efficiency. For the next step, we are going to confirm the performance of whole system with multi-line operation and extend to 4 lines. We believe the stable performance and high efficiency 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 extraction efficiency of each element to obtain more stable and higher laser power.

6. ACKNOWLEDGEMENTS

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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).

[6] Junichi Fujimoto, Takeshi Ohta, Krzysztof Nowak, Takashi Suganuma, Hidenobu Kameda, Masato Moriya, Toshio Yokoduka, Koji Fujitaka, Akira Sumitani, Hakaru Mizoguchi, "Development of the reliable 20 kW class pulsed carbon dioxide laser system for LPP EUV light source," Proc. SPIE Vol. 7969-99, 79692S (2011).