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ABSTRACT

In this paper, we provide a detailed review of development of a highly-efficient high-power nanosecond pulse CO_2 laser using transverse-flow radio-frequency (RF)-exited laser amplifiers, which is for extreme ultraviolet (EUV) light source of a next generation of nano-lithography. High-density excited high-power transverse-flow CO_2 lasers were designed and built for the application of laser produced plasma (LPP) EUV source. We carried out an amplification test of the transverse-flow CO_2 laser seeded by a nanosecond pulse CO_2 laser. A four-amplifier system generated an average output power of 21 kW with an electrical input power of 400 kW for discharges. The electrical-to-optical efficiency was 5.2%. The input pulse laser had an average power of 46 W, the repetition rate was 100 kHz, and the pulse duration was 15 ns. The transverse-flow CO_2 laser has strong points in high gain and availability of the multi-fold optical path. A highly-efficient amplification was experimentally proved characterized by transverse-flow CO_2 laser amplifiers even with low-power seed. A transverse-flow CO_2 laser is a promising candidate for an amplifier in the LPP EUV light source.

Keywords: EUV source, Laser produced plasma, pulse CO_2 laser, CO_2 laser amplifiers, transverse-flow CO_2 laser

1. INTRODUCTION

Extreme ultraviolet (EUV) lithography at 13.5 nm is going to be the next critical dimension imaging solution after currently used immersion lithography with 193 nm argon fluoride excimer laser sources. CO_2 laser produced tin plasma (LPP) is the promising candidate as the 13.5 nm high power light source for EUV lithography[1,2]. In this EUV source, tin droplets are irradiated with a high-power pulsed CO_2 laser beam, and generate EUV light. The availability of a high-power source for 13.5 nm radiation has been considered as a key issue to enable the high-volume manufacturing using EUV lithography. Therefore, the development of a high power pulsed CO_2 laser system is highly demanded and a number of systems have been developed in recent years. The EUV source requires the laser driver to produce an average laser power of at least 20 kW, a repetition rate in excess of tens of kilohertz, and a pulse duration of 15–20 ns to achieve an over 200 W clean EUV power[3].

The recent needs of LPP EUV light sources accelerated the master oscillator power amplifier (MOPA) CO_2 laser technology toward kilowatts level average power. According to the references[4], axial-flow radio-frequency (RF)-excited CO_2 lasers were used as the amplifier and output power of over 10 kW[5] with the repetition rate in excess of tens of kilohertz were demonstrated. Selections of amplifiers become limited for constructing a tens-of-kilowatt short-pulse MOPA CO_2 laser system. The amplifier unit must provide a CW output power of more than about 10 kW supposing that it is used as an oscillator. Otherwise tens of amplifier units are needed to construct a high-power laser system beyond 20 kW so that the system will be too complicated. Two types of CO_2 laser have the capacity of providing high power described above. One is (fast-) axial-flow CO_2 laser demonstrated in the late 1960s, and the other is transverse-flow CO_2 laser suggested and demonstrated during the same period. Both types have been sophisticated and are now commercially available as light sources for material processing including metal cutting and welding.

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LPP EUV source is a system requiring a lot of electricity. The electrical to optical efficiency of the CO_2 laser system is several percent, and the conversion efficiency from CO_2 laser to EUV emission is also several percent. Megawatts level of electricity is used to generate a 200-W EUV power. High-efficiency technologies saves huge amount of electricity. Authors have made a proposal of transverse-flow CO_2 laser amplifiers as one of these technologies based on the inherent advantage of higher small signal gain compared to that of the axial-flow laser[6]. The transverse-flow CO_2 laser has a strong point also in availability of the multi-fold optical path. The actual proof of short-pulse amplification has been continuing issue to be used for EUV generation. In this paper, we provide a detailed review of development of a highly-efficient high-power nanosecond pulse CO_2 laser using transverse-flow RF-exited laser amplifiers. A prototype configuration is described including four transverse-flow CO_2 laser amplifiers in cascade. In the first amplifier, five-fold optical path was adopted to enhance the gain. Several results of amplification test are discussed.

2. PARAMETER STUDY

Two types of CO_2 laser amplifiers have the capacity of providing high power for high volume manufacturing EUV source. One is (fast-) axial-flow CO_2 laser and the other is transverse-flow one. Both types are now commercially available as laser oscillators for material processing including metal cutting and welding. The parameter study is described here between commercial high-power transverse-flow and axial-flow CO_2 lasers.

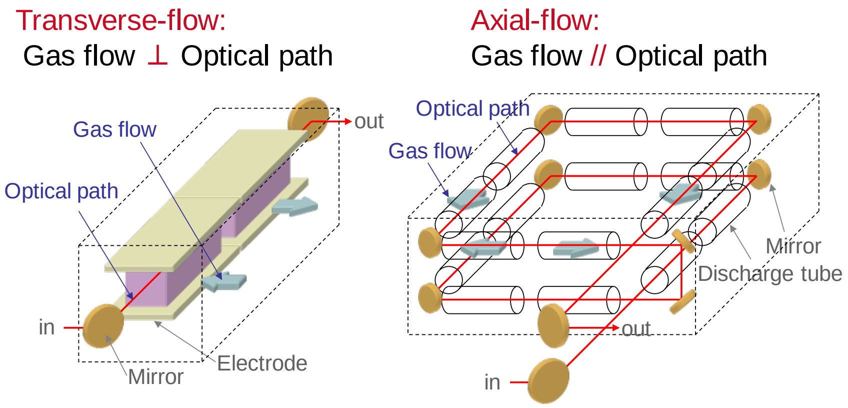


Figure 1. Structural drawing of a transverse-flow CO_2 laser amplifier and of an axial-flow CO_2 laser amplifier. The directions of laser gas flow are shown as three-dimensional arrows. In the transverse-flow laser, the direction of the gas flow is perpendicular to the direction of the optical path. In the axial-flow laser, the direction of the gas flow is parallel to the direction of the optical path.

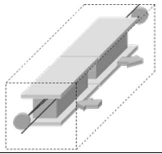
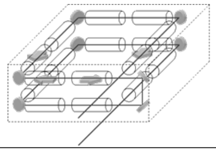
The laser gas flow directions are totally different in these two types of CO_2 laser amplifiers. Figure 1 shows the structural drawing of a transverse-flow CO_2 laser amplifier and of an axial-flow one. In the transverse-flow CO_2 laser, the laser gas is excited between the electrodes facing each other. The gas is circulated by blowers and chilled by radiators. The direction of the gas flow is perpendicular to the direction of the optical path. The amplifier has two pairs of electrodes and the direction of the gas flow in a pair of electrode is opposite to that in the other. This configuration cancels asymmetry of the laser beam profile. On the other hand, in the axial-flow CO_2 laser, the laser gas is excited inside the discharge tubes. The gas is also circulated by blowers and chilled by radiators. The direction of the gas flow is parallel to the direction of the optical path.

Table 1 describes our parameter study between commercial high-power transverse-flow and axial-flow CO_2 lasers. A transverse-flow CO_2 laser having CW output power of 4 kW and a 5-kW axial-flow CO_2 laser are compared. Each laser is major product in own laser gas flow type and is widely spread in the world for material processing including metal cutting. The output powers of these lasers are about the same. The gas flow cross-section of the transverse-flow laser is over a magnitude larger than that of the axial-flow laser. Thus it is easy in the transverse-flow laser to reduce the laser gas temperature increasing in the discharge area. The transverse-flow CO_2 laser works with the slower laser gas flow, the smaller heat capacity of the laser gas, and the lower gas pressure compared with the axial-flow laser. The small signal gain is inversely proportional to the laser gas pressure because of pressure broadening. Therefore the transverse-flow CO_2 laser has higher small signal gain than the axial-flow one. Each gain in table 1 was estimated by the classical laser oscillation model expressed below.

$$P = P_S\left(g_0 L + \ln\sqrt{1-r}\right) \tag{1}$$

where P is the output power, P_S is the saturation power, g_0L is the small signal gain, and r is the cavity loss. The small signal gain of 4-kW transverse-flow CO_2 laser was estimated to be 3.7, and that of 5-kW axial-flow CO_2 laser was estimated to be 2.2. The high gain is a strong point in the transverse-flow CO_2 laser amplifier.

Table 1. Comparison between parameters of commercial high-power transverse-flow and axial-flow CO_2 lasers. A transverse-flow CO_2 laser having CW output power of 4 kW and a 5-kW axial-flow CO_2 laser are compared.

	Transverse-flow (4 kW)	Axial-flow (5 kW)
		
Gas flow cross-section	700 cm^2	40 cm^2
Gas pressure	7 kPa	20 kPa
Small signal gain	3.7	2.2
Multi-fold path	Possible	Impractical

Here we discuss the amplification when the input laser power is large enough. The extraction power, the difference between the output power and the input power, is proportional to the stored energy in the upper level ($CO_2(001)$) E_{band}, and to the rotational relaxation utilization ratio η_{rot}. Only a portion of energy in the upper level is extracted in nanosecond pulse amplification because the rotational relaxation time in the upper level is the order of nanosecond. η_{rot} means this portion. The relation between the saturation pulse energy E_S and $E_{band}\eta_{rot}$ is shown in the expression (2).

$$E_S = \eta_{rot}\frac{E_{band}/V}{g_0} \tag{2}$$

where V is the discharge volume. The transverse-flow laser offers high amplification efficiency when the input laser power is lower than the rated oscillation power (several kW), which enhances the amplification efficiency is the system.

It is possible to make multi-fold optical path in the transverse-flow CO_2 laser as shown in table 1. For example, a triple-fold path is installed in the 4-kW transverse-flow CO_2 laser. The multi-fold optical path greatly enhances the optical power especially when used in the first amplifier because the input power is the order of 10 watts. The transverse-flow CO_2 laser has the potential of highly-efficient amplification as explained above.

3. SINGLE AMPLIFIER EXPERIMENT

3.1 Method

A prototype transverse-flow RF-excited CO_2 laser amplifier was designed and built for the LPP EUV source. The electrical input for the discharge was up to 100 kW. An electro-optic Q-switched cavity-dumped CO_2 laser was used for the master oscillator. Figure 2 shows a schematic diagram of the experimental setup consisting of the oscillator, an isolator unit, beam delivery optics, and the amplifier. A pulsed laser beam generated by the master oscillator was amplified by the transverse flow CO_2 laser medium.

The Q-switched cavity-dumped CO_2 laser emitted 13-ns, single-line (P20) laser pulses. The isolator inhibits global self-oscillation caused by coupled gain of the master oscillator and the amplifier. This isolator was on the basis of "time window" using cadmium telluride electro-optic switches. It allows the transmission of beams only when the switches are on.

The amplifier had two discharge areas arranged in series. The laser gas flew in opposing direction with each discharge area to minimize the laser pointing displacement caused by the gas temperature gradient across the beam. Each discharge area had a length of 937.5 mm, a discharge gap of 50 mm respectively. A radio-frequency power source excited the laser gas. The total electrical input for the discharge was up to 100 kW. The gas pressure was 7.0 kPa. The gas flow rate in the discharge area was adjusted to 100 m/s. The amplifier had a five-fold optical path. The reflecting mirror in the amplifier was set to make a small angle with each other, which avoided an undesirable parasitic oscillation between two mirrors.

In the amplification test, the master oscillator worked at the repetition rate of 100 kHz and the pulse duration of 13 ns FWHM (full width at half maximum). The input power to the amplifier was up to 8.5 W and adjusted using a combination of a half wave plate and a thin film polarizer. The beam from the oscillator was collimated using three lenses so that a $1/e^2$ radius of the beam in the amplifier was approximately 6 mm. The amplification test was carried out at a 100% duty cycle of discharge. The input laser power measured just before the amplifier window was up to 8.5 W.

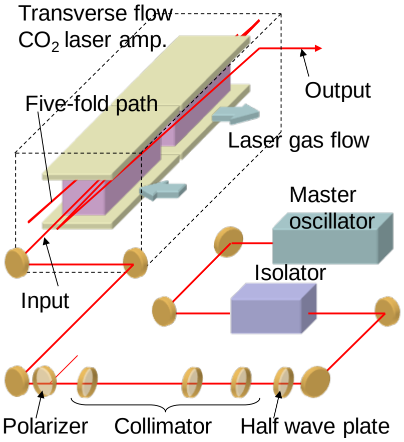


Figure 2. Configuration of the experimental setup.

3.2 Results

The measured average output power is shown in Fig. 3 as a function of the optical input power into the amplifier when the electrical power for the discharge was 100 kW. The output power increases as the input power increases toward saturation. We obtained 3.07 kW at an input power of 8.5 W. Thus the electrical-to-optical efficiency (= (output power – input power) / electrical input for the discharge) was 3.1%. We also measured the output power from the running amplifier without any input beams to investigate the background part caused by self-oscillation. The measured output power was 12 W at the electrical input power of 100 kW. The background power was at least hundredths part of the signal power.

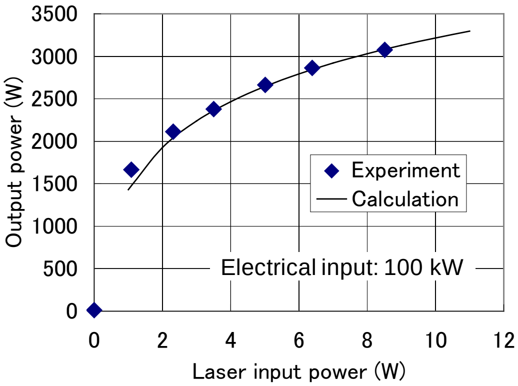


Figure 3. Measured output power versus input laser power for the amplifier.

Figure 4 shows temporal pulse intensity profiles of the input and amplified laser pulse measured in the condition that the average amplified power was 3.07 kW. The pulse showed a slight stretch from input duration of 13 ns FWHM to output of 15 ns. The initial intensity rise pointed by the arrow in Fig. 4 corresponds to the turn-on of the isolator. Pictures in this figure are beam profiles measured behind the output window of the amplifier with the amplifier off using a pyroelectric camera (a) and with the amplifier on by burning an acryl board (b), shown with a side view. The transverse mode of amplified beam matched up nicely with that of beam when the amplifier off. The measured beam quality factor M^2 of the input laser beam was 1.4.

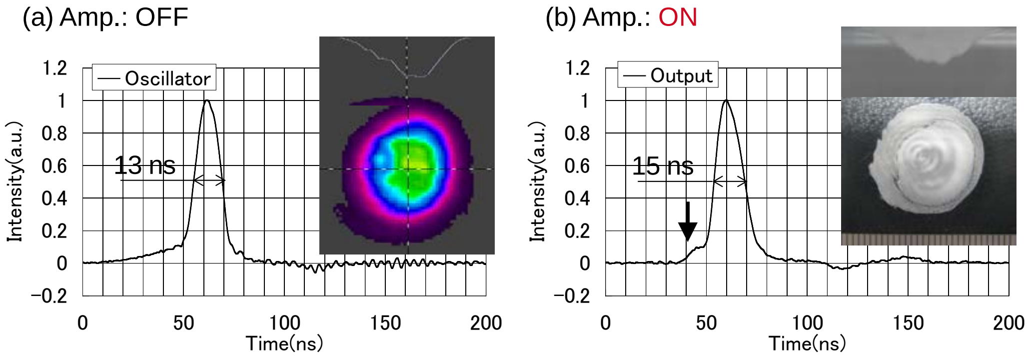


Figure 4. Measured temporal pulse profiles of input and amplified output laser. Pictures are beam profiles measured behind the output window of the amplifier. (a): measured with the amplifier off, by a pyroelectric camera, (b): measured with it on, by acrylic burn patterning

4. FOUR-AMPLIFIER SYSTEM

4.1 Configuration

A prototype high-power pulsed CO_2 laser system was designed and built consisting four transverse-flow amplifiers in cascade. A schematic view of this prototype is shown in Figure 5, and a picture is Figure 6. The pulsed laser from the master oscillator went through the isolator unit and was amplified by four amplifiers. The isolator unit contains time window isolator and collimator optics.

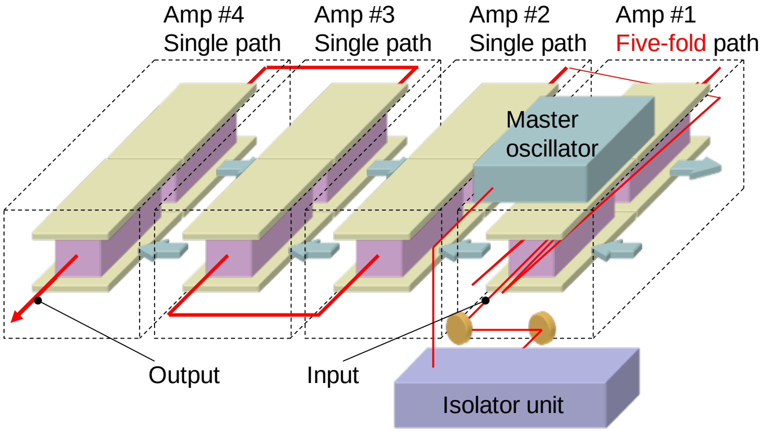


Figure 5. Schematic diagram of the prototype high-power pulsed CO_2 laser system.

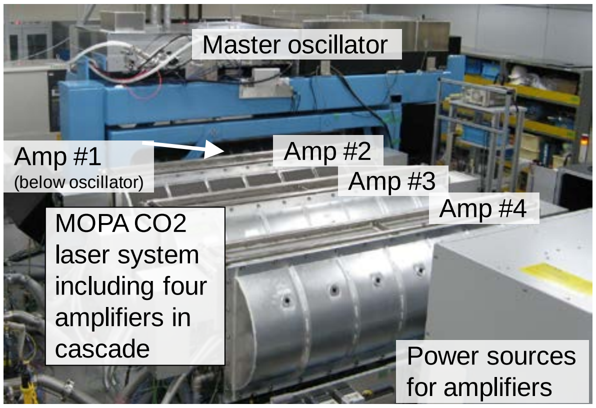


Figure 6. Picture of the prototype high-power pulsed CO_2 laser system.

Table 2. Conditions of the amplification test with the prototype high-power laser system.

Master Oscillator	
Wavelength	10.6 mm P(20)+P(22)
Repetition frequency	100 kHz
Pulse duration	15 ns
Amplifiers	
Laser input	46 W max
Beam radius($1/e^2$)	≒6 mm@amp#1 , ≒15 mm@amp#2-4
Electrical input	100 kW max x4
Discharge duty	33%
Discharge volume	5x4x188 cm^3 x4
Gas pressure	7.0 kPa

The master oscillator was provided by Gigaphoton Inc. and emitted two lines (P(20) and P(22)) simultaneously. The pulse repetition frequency was 100 kHz and the pulse duration was around 15 ns. The amplifier #1 is the same as described in the preceding section and has a five-fold optical path. The other amplifiers have a single path. Conditions of the amplification test are shown in Table 2. The $1/e^2$ radius of the beam was approximately 6 mm in the amplifier #1 and about 15 mm in the amplifier #2 to #4. The electrical input for the discharge was up to 100 kW for each amplifier. The amplification test was carried out at a 33% duty cycle of discharge. The input laser power measured just before the amplifier window was up to 46 W.

4.2 Result and discussion

The output power was measured as a function of electrical power for the discharge. Figure 7 displays the measurement result. The output power increased smoothly as the electrical power increased. An average output power of 21 kW was achieved with a total electrical power 400 kW discharge. The electrical-to-optical efficiency was 5.2%. Good stability of the output pulse was recorded. The duration of output pulse was 23 ns. From the measured temporal pulse profiles, it was confirmed that there was few CW part in the pulse amplification. As a result of amplification with three axial-flow lasers, the available CO2 laser power of 12–15 kW was reported with the radiofrequency input power of 140 kW per amplifier[5]. According to this data, it can be presented that more efficient amplification was achieved by the transverse-flow CO_2 laser amplifiers. Detailed evaluations are under study such as input-output characteristics in the single optical path amplifier and long term reliability.

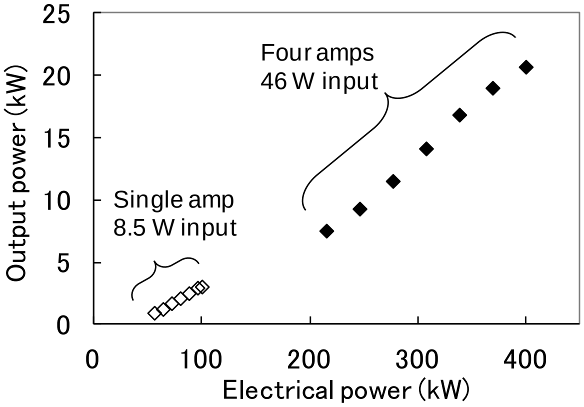


Figure 7. Measured output power versus electrical power for the discharge in the four-amplifier prototype system is plotted along with the data of single amplifier test.

5. SUMMARY

High-efficiency technologies saves huge amount of electricity in the laser produced plasma EUV light source. A CO_2 laser power of 21 kW with the electrical-to-optical efficiency of 5.2% in the amplification has been reported. This highly-efficient CO_2 laser is characterized by a technology of transverse-flow CO_2 laser amplifiers. The output power was delivered by a four-amplifier system with a total electrical power 400 kW discharge. The master oscillator was provided by Gigaphoton Inc. and emitted two lines (P(20) and P(22)) simultaneously. The input pulse laser had an average power of 46 W, the repetition rate was 100 kHz, and the pulse duration was 15 ns. The transverse-flow CO_2 laser has strong points in high gain and availability of the multi-fold optical path. A highly-efficient amplification was experimentally proved characterized by transverse-flow CO_2 laser amplifiers even with low-power seed. A transverse-flow CO_2 laser is a promising candidate for an amplifier in the LPP EUV light source. Detailed evaluations are under study such as input-output characteristics in the single optical path amplifier and long term reliability.

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REFERENCES

[1] Tanaka, H., Akinaga, K., Takahashi, A. and Okada, T., “Emission characteristics of EUV light source by CO_2 laser-produced Xe and Sn plasma,” Proc. SPIE 5448, 737-748 (2004).

[2] Ueno, Y., Soumagne, G., Sumitani, A. and Endo, A., “Enhancement of extreme ultraviolet emission from a CO_2 laser-produced Sn plasma using a cavity target,” Appl. Phys. Lett. 91, 231501 (2007).

[3] Ohta, T., Nowak, K. M., Suganuma, T., Kameda, H., Moriya, M., Yokoduka, T., Kawasuji, Y., Fujimoto, J. and Mizoguchi, H., "Development of the reliable high power pulsed carbon dioxide laser system for LPP EUV light source," Proc. SPIE 8322, 83222O (2012).

[4] Brandt, D. C., Fomenkov, I. V., Ershov, A. I., Partlo, W. N., Myers, D. W., Böwering, N. R., Bykanov, A. N., Vaschenko, G. O., Khodykin, O. V., Hoffman, J. R., Vargas, L. E., Simmons, R. D., Chavez, J. A. and Chrobak, C. P., "LPP EUV source development for HVM," Proc. SPIE 6517, 65170Q (2007).

[5] Brandt, D. C., Fomenkov, I. V., Farrar, N. R., La Fontaine, B., Myers, D. W., Brown, D. J., Ershov, A. I., Sandstrom, R. L., Vaschenko, G. O., Bowering, N. R., Das, P., Fleurov, V. B., Zhang, K., Srivastava, S. N., Ahmad, I., Rajyaguru, C., De Dea, S., Dunstan, W. J., Baumgart, P., Ishihara, T., Simmons, R. D., Jacques, R. N., Bergstedt, R. A., Porshnev, P. I., Wittak, C. J., Rafac, R. J., Grava, J., Schafgans, A. A., Tao, Y., Hoffmann, K., Ishikawa, T., Evans, D. R. and Rich, S. D., "CO_2/Sn LPP EUV sources for device development and HVM," Proc. SPIE 8679, 86791G (2013).

[6] Tanino, Y., Yamamoto, T., Nishimae, J. and Fujikawa, S., Opt. Lett. 37, 3300-3302 (2012).