High Power Pulsed CO_2 Laser for EUV Lithography

Tatsuya Ariga, Hideo Hoshino, Taisuke Miura and Akira Endo
EUVA (Extreme Ultraviolet Lithography System Development Association),
1200 Manda Hiratsuka, Kanagawa, 254-8567, Japan

ABSTRACT

Laser produced plasma is the candidate for high quality, 115 W EUV light source for the next generation lithography. Cost effective laser driver is the key requirement for the realization of the concept as a viable scheme. A CO_2 laser driven LPP system with a Xenon or Tin droplet target, is therefore a promising light source alternative. We are developing a high power and high repetition rate CO_2 laser system to achieve 10 W intermediate focus EUV power.
High conversion efficiency (CE) from the laser energy to EUV in-band energy, is the primarily important issue for the concept to be realized. Experimental and numerical simulation analysis of a Xenon plasma target shows that a short laser pulse less than 15 ns is necessary to obtain high CE by a CO_2 laser. This paper describes on the development of a CO_2 laser system with a short pulse length less than 15 ns, a nominal average power of a few kW, and a repetition rate of 100 kHz based on RF-excited, axial flow CO_2 laser amplifiers.
Output power of 1 kW has been achieved with a pulse length 15 ns at 100 kHz repletion rate in a small signal amplification condition. The phase distortion during the amplification is negligible and the beam is focused down to 100 μ m diameter onto a fast Xenon jet. The conceptual design of the CO_2 laser system for LPP EUV light source, and amplification performance in short pulse using RF-excited axial flow laser as amplifiers, are reported. Additional approach to increase the amplification efficiency is discussed.

Keywords: EUV, Laser Produced Plasma, CO_2 Laser, axial flow

1. INTRODUCTION

Pulsed CO_2 laser systems have been useful tools for various applications ranging from material processing of metals, glass, ceramics and epoxy, paint removal, medical, spectroscopy, to generation of laser produced plasmas as UV, EUV and soft X-ray sources. One of the drawbacks is the limited repetition rate once TEA CO_2 lasers are employed. The other drawback is the limited controllability of the pulse width in case of low pressure microwave excitation lasers. Attempts were reported a decade ago on the trials to operate microwave excited CO_2 laser modules in a Q-switched oscillator mode [1)] and an oscillator-amplifier mode [2)]. Typical performances were 170 mJ, 250 ns, 4 kHz, and 680 W average power for the former case, and 70 mJ, 35 ns, 10 kHz, and 800W average power for the latter experiment. CW output powers were 2 kW, and 7 kW, respectively. Laser efficiencies were not high enough in both cases in the short pulse mode.
Recent experimental and theoretical works have revealed that the wavelength dependence of the conversion efficiency from the input laser power to the generated EUV in-band power (CE :conversion efficiency) is weak for Xenon and Tin targets after optimization is properly performed [3)]. Most of the EUV plasma experiments have been performed in the past by using solid state lasers, namely Nd:YAG in ns region, or Ti:Sapphire lasers in ps and fs regions [4)]. Some experiments were by excimer lasers combined with cluster Xenon jets [5)]. The power requirement in the commercial EUV light source, which is 115 W, 13.5 nm, 2 %bandwidth, at the intermediate focus, combined with 1 % CE, caused a serious reconsideration on the usable laser driver for the final commercial EUV light source. LPP (Laser produced plasma) approach is superior compared to GDPP (Gas discharge produced plasma) in terms of lower debris, higher controllability of plasma, smaller plasma size, higher collection efficiency of generated EUV light. But the requirement for the laser driver average power up to 30 kW in ns pulsed mode, is the most critical factor which may hinder the LPP reality in the commercial field. It is still possible to assume to employ a solid state laser system in this power range, but there are many obstacles to the realization of the laser system. Typical rod amplifiers are characterized in high average power operation by high thermal distortion of the gain medium, which is relating to the deterioration of the polarization of the beam, worse focusability, and damage to the optical surfaces inside the laser system [6)]. Efforts to overcome the heat distortion are continued by new laser materials like Yb:YAG and new configuration like thin disc or fiber, and

developing fast in CW regime into multi kW regions [7, 8]. The possibility to operate these lower thermally distorted lasers in pulsed mode, is limited in the single pulse energy. A large thin slab amplifier is emerging as an alternative for the high average power amplifier, but bulky laser diodes and focusing optics are the origins of the main cost of the laser [9]. CW CO_2 lasers are most frequently used lasers in industry due to its lower initial and operational costs, robustness, environmental safeness, and reliability. Some CO_2 lasers are operated in long pulsed mode depending on the applications. RF excitation is the most commonly employed scheme in axial flow or conduction cooled Slab or waveguide configurations. The design guideline of the multi kW short pulse CO_2 laser system is described in this paper to realize a high repetition rate, high pulse energy, high amplification efficiency, high beam quality, by using commercial high average power CO_2 laser modules as amplifiers, especially as the main energy injector of EUV plasma.

2. CONCEPTUAL DESIGN

2.1 Xe droplets and CO_2 laser

There are two choices as the EUV emitter, namely Xenon or Tin. Xenon is inert and free from contamination with up to 1 % CE, and Tin is difficult to handle in a clean environment but with higher CE more than 2%. Target supply is one of the key technologies in the EUV source design. Minimum target material must be supplied in the exact time and position to be irradiated by pulsed laser efficiently. The vacuum environment must be kept high to avoid self absorption of the generated EUV light on the path to the intermediate focus. Present method for the target supply is Xenon droplet in our experimental setup [10]. A cryogenic system combined with a nozzle generates a Xenon liquid jet with a diameter around 10 to 20 µm. A piezo electric element (PZT) attached to the nozzle induces a Rayleigh instability that causes the jet to break up into droplets. The droplets are first generated in a low vacuum environment for stabilization, and then enter into high vacuum chamber through a small aperture. Tin target is shown to have a high CE by single, long pulse CO2 laser irradiation [11]. But a few conditioning of the plasma is necessary for high CE realization from Xenon target, based on the atomic and plasma properties. Optimization of the density and expansion of the plasma is possible by a pre-pulse of a small solid state laser pulse, and delay and pulse width control of the main laser pulse (CO_2 laser). The Xenon droplets (30 µm) have been irradiated by a solid state pre-pulse (5 mJ, 6 ns), and CO_2 main pulse (60 mJ, 25 ns). The CE was measured as 0.6 % with a time delay of 200 ns. A controller synchronized the droplet generation frequency with the laser pulses. Theoretical works indicate further CE increase depending on the pulse width [12].
A short pulse TEA CO_2 laser system was developed for basic study purpose in our laboratory. Three excimer lasers were converted into CO_2 laser modules by replacement of the electrodes and windows. The first one was equipped with a CdTe EO switch to generate 25 ns, 20 mJ pulses by Q-switching. The generated pulses were amplified in two other modules by multi pass configuration to obtain 25 ns, 200 mJ, $M^2 = 1.9$ pulses. The repetition rate was limited up to 2kHz due to the atmospheric gas clearance of the discharge region. The 25 ns CO_2 laser system was connected with a 6 ns, Nd:YAG laser and a Xenon droplet generator, and the experimental results are described in our previous paper [13].

2.2 Concept of the CO_2 laser amplifier system (Master Oscillator and Power Amplifier (MOPA) system)

Successful experiment on the high CE realization was the starting point of the conceptual study of the laser driver based on available high power laser modules. A small energy solid state laser is the necessary component of the whole laser driver. The pointing and focusing accuracy must be in the range of 10 µm. Pulse energy is around 5mJ with short pulse width down to sub ns region. The system repetition rate is set at 100 kHz to achieve high amplification efficiency of the main CO_2 amplifier. A thin disc Yb:YAG laser, which is characterized by high average power, high beam quality, high efficiency, was selected for this purpose. A modification of a CW 1 kW laser is on schedule to achieve the required specification as a pre-pulse laser. An accompanying paper describes on technical details [14]. A Yb:glass mode-locked laser is employed as the signal standard of the whole system with 0.25 ps pulse width. The pulse is stretched by a fiber up to 1ns, and seeded into the Yb:YAG thin disc regenerative amplifier cavity. A part of the short pulse Yb:YAG pulse is sliced to be used to generate a broadband seed to control the CO_2 laser spectrum. A combination of a pulse compressor, OPA and DFG crystals generates a broadband 10 µm light with 1 µm band width. CO_2 laser chain is composed of four laser modules, namely 15 ns and 100 kHz short pulse seeder, two pre- amplifiers with tube inner diameter 17 mm, and a main amplifier with tube inner diameter 30 mm of fast axial flow, RF pumped lasers.
Figure.1 shows the overall configuration of the laser driver system, best fitting to 10 µm Xenon droplet target at 100 kHz repetition rate. Figure.1 is composed of an oscillator, two pre-amplifiers and one main amplifier.

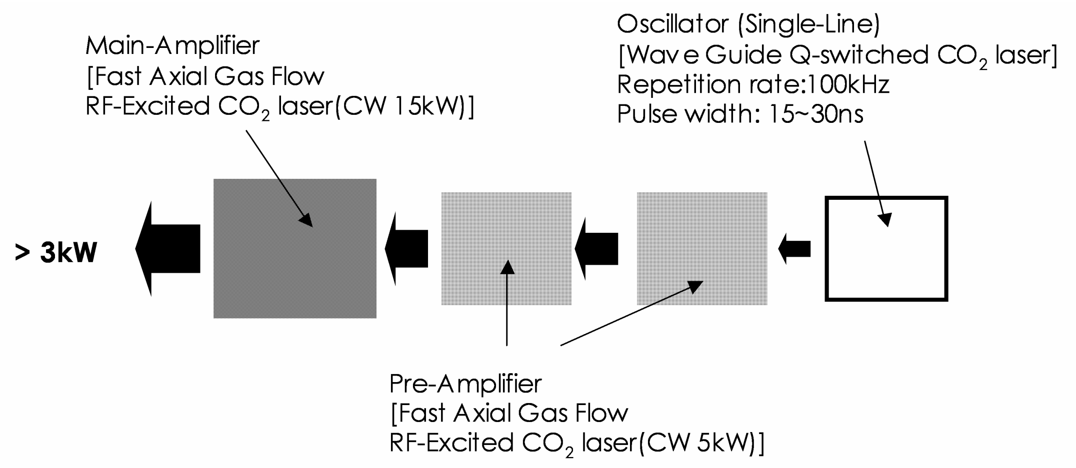

Figure.1 Configuration of the laser driver for the Xenon droplet target LPP EUV light source

3. EFFICIENT AMPLIFICATION OF SHORT PULSE IN CO_2 MEDIUM

3.1 Characterization of low pressure CO_2 laser medium

The gain medium in CO_2 lasers is a CO_2:N_2:He gas mixture with pressures from 10 Torr to 10atmosphere depending on the excitation method. Low pressure system is employed in CW or fast repetition rate pulse system by RF excitation, and high pressure system is used for low repetition rate or single shot, high pulse energy applications by TEA discharge or electron beam excitations. The important relaxations are vibrational and rotational relaxations of the 00^01 band (τ_c and τ_r). These are typically 0.5 μsec and 1.5 ns in 100 Torr gas mixtures, respectively. The pulse train is composed of 10 ns pulses with 10 μsec time intervals. Thus the vibrational relaxation time is substantially longer then the pulse duration (τ_p), which implies that the amplification is only through the inversion built up in the main vibrational band during the pulse interval. The pulse duration is longer than the rotational relaxation time by less than an order of magnitude. Some contribution of the rotational relaxation must be considered in the pulse amplification. Considerable theoretical and experimental works have been performed for the development of TEA or multi atmospheric amplifiers designed for amplification of 1ns and down to 10 ps short pulses. The ratio of pulse width and relaxation time is $\tau_p/\tau_r \sim 10$ both in 1ns pulse amplification in 1 atmospheric gas mixture, and in 10 ns pulse amplification in 100 Torr gas mixture. It is thus useful to consider on the amplification study of 1ns pulses in a 1 atmosphere gas mixture, to estimate the behavior of the extraction efficiency of the 10 ns pulses in 100 Torr gas mixture. A numerical result is shown on a single pass amplifier of L=1 m long on the P(20) line in Fig.2 [16)]. E_{in} is the input pulse fluence in mJ/cm^2, E_{out} is the output fluence, E_{max} is the maximum fluence given by $g_0 \cdot L \cdot E_s$, where $g_0$is the small signal gain coefficient in cm^{-1} , L is the gain length, and E_s is the saturation fluence in mJ/cm^2 . g_0 and E_s are functions of various parameters, namely gas pressure, mixture ratio, excitation density, pulse repetition rate, and input pulse spectrum. The Frantz-Nodvik equation describes the amplification in pulsed amplification.

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

More than 70 % of the available fluence is possible with $\tau_p / \tau_r = 11.6$ in the strong saturation amplification. Typical electrical efficiency of an axial flow CO_2 laser is around 20 % in CW oscillation, thus the expected maximum efficiency in a pulsed mode is more than 10 % after optimization.

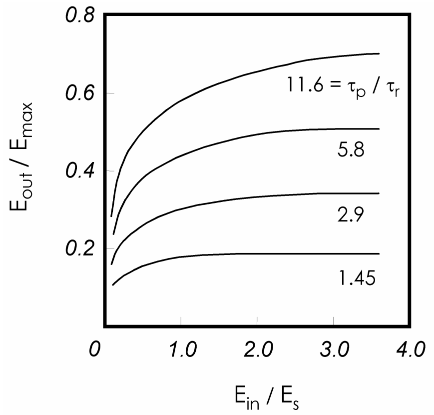

Figure.2 Calculated power extraction vs. pulse energy relations plotted for different values of the τ_p/τ_r parameter (τ_p = 1 ns, P(20)) [16].

3.2 Short pulse amplification of CO_2 laser MOPA system

Commercially available RF pumped fast axial flow CW 5 kW (two units) and 15 kW (one unit) lasers were installed in our laboratory for test purposes. And the lasers are 13.56 MHz RF-excited fast axial flow CW lasers. Cavity mirror set for each laser is exchanged with ZnSe windows and lasers were modified as amplifiers.

For the 5 kW laser, the standard gas composition is CO_2:N_2:He=5:29:66 around 120 Torr gas pressure. Axial gas flow speed is fast enough to keep the laser gas temperature inside the operational condition. Unit length of the gain region is 15 cm, and 16 active cylindrical gain regions are connected in series. The total internal length of the optical pass is about 590 cm. The tube inner diameter is 17mm. The laser operates at 5 kW CW output power with M^2 =1.8 beam quality as an oscillator with input electrical power of 36 kW.

For a 15 kW laser, the standard gas composition is CO_2:N_2:He=2:10:48 around 150 Torr gas pressure. Unit length of the gain region is 28 cm, and 16 active cylindrical gain regions are connected in series. The total internal length of the optical pass is 890 cm. The tube inner diameter is 30 mm. The maximum electrical input power is 88 kW.

Two CW 5 kW lasers were used as pre-amplifiers and one CW 15 kW laser was used as the main-amplifier as shown in Fig.1(a) for short pulse amplification. Special consideration is required to achieve efficient short pulse amplification in CW pumped gain modules. Parasitic oscillation inside the gain region, or optical coupling between two amplifier modules are typical problems in short pulse amplification in CW pumped gains. The gain region is not seeded by 10 ns amplifying laser pulses during 10 μsec. Spontaneous emission could grow to a large signal to deplete the gain. An experiment was performed to confirm optical coupling without seeding. The oscillator laser in the CW amplification experiment was converted into a pre- amplifier by changing windows as transmit ones. A power detector was set at the output window of the second and third amplifiers to measure a stray amplification. There was no power signal at full RF pumping of two pre-amplifiers and one main amplifier lasers based amplifiers, which indicated no parasitic oscillation and optical coupling without seed laser pulse.

A compact, short pulse oscillator was installed as the seeder for the amplifiers. The laser was an EO Q-switched, 15 ns, single P(20) line, 100kHz, RF pumped waveguide CO_2 laser with 5 W output. Figure.1 shows the experimental arrangement of the 100 kHz laser system. 1kW was achieved by two pre-amplifier and a main amplifier amplification with seed power of 5 W. The short pulse amplification performance of the second pre-amplifier and the main amplifier have been estimated by amplification result using the Frantz-Nodvik equation. Figure.3 shows the short pulse MOPA system amplification performance by two pre-amplifiers and the main amplifier that uses estimated gain g_0 and saturation energy E_s of the pre-amplifier and main amplifier with 1 kW test result. The available output power is estimated from the present RF-excited MOPA system by use of a high power and short pulse Q-switched waveguide oscillator. A short pulse (pulse width in FWHM : < 30 ns), output power over 80 W and repetition rate of 100 kHz oscillator is installed into the system recently. A mode matching is very important for efficient power extraction, i.e. input beam profile has to match with the gain cross section of each amplifier. The seed laser beam diameter is expanded respectively in pre- and main amplifiers. The calculation result shows that 3 kW of the system output power is able to be achieved by a seeding power of 60 W in P(20) single mode amplification. Further power increase is envisioned by further optimization and a multi-line amplification scheme up to 10 kW.

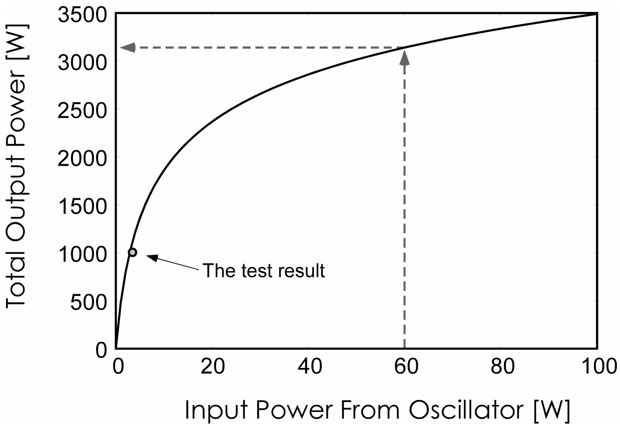

Figure.3 Output power estimation of the RF-excited MOPA system by use of a short pulse 60 W input power from an oscillator. The amplification test result with 1 kW output is plotted.

When there is a pedestal or tail in the input laser pulse, the pedestal and tail of the amplified laser pulse increases compared to the seed pulse. This means that the laser gain is used for amplification of the pedestal. Therefore, the reduction of the pedestal is necessary for effective short pulse amplification. Pedestal of the seed laser pulse is able to be removed by use of CdTe Pockels Cell with a polarizer or saturable absorber gas cell which contains SF_6 [17)]. Figure.4 shows the time profile of laser pulses. In Fig.4, “Osc” is a time profile of the EO Q-switched CO_2 laser that was used as an oscillator. “Osc+Pre#1”, “Osc+Pre#1+Pre#2” and “Osc+Pre#1+Pre#2+Main” are amplification results with “first pre-amplifier”, “first pre-amplifier + second pre-amplifier” and “first pre-amplifier + second pre-amplifier + main amplifier”, respectively. A slight pedestal was accompanying before the main 15 ns pulse for 200 ns duration with 15 % energy of the main pulse when the oscillator pulse was amplified with the first pre-amplifier, the second pre-amplifier and the main amplifier. This means that there is a very slight pedestal on the oscillator initially.

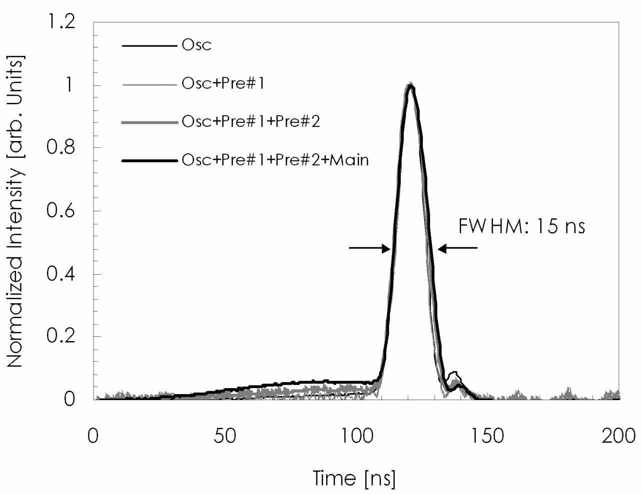

Figure.4 Input pulse of the EO Q-switched CO_2 oscillator and amplified laser pulses after each stage

Figure.5 shows the dependence of output pulse energy from pre-amplifier and main amplifier on the repetition rate of the laser system. The dependence of amplified pulse energy on the repetition rate is stable in 50 ~ 130 kHz laser condition. The result is reasonable in the small signal gain amplification region and means no amplification saturation.

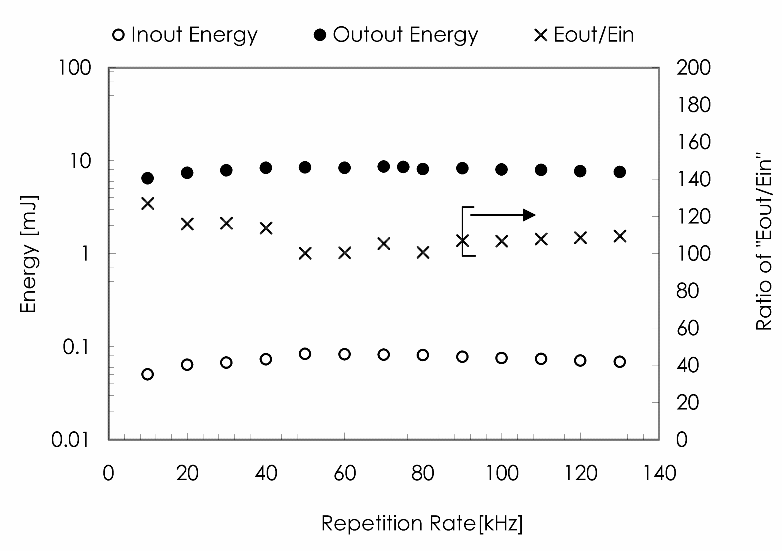

Figure.5 Dependence of amplified pulse energies on the repletion rate of the laser system

3.3 Beam quality of short pulse amplification

M^2 was estimated by focusing characteristics measurement[18]. The focusing characteristics were measured by focusing the short pulse beam with a focusing lens of F=127mmand measuring the beam size dependence on the distance from the lens. Measurement result of the short pulse oscillator laser "Before Amplification", and the amplified short pulse laser beam by two pre-amplifiers and the main amplifier "After Amplification", are shown in Fig.6. There is no difference of the focusing characteristics between "Before Amplification" and "After Amplification". This means that phase distortion of amplifiers are small enough for amplification in this laser system. Beam waist of "Osc" and "System" are both below 0.1mm and M^2 of the oscillator and the amplified beam have been both estimated as close to 1.0.

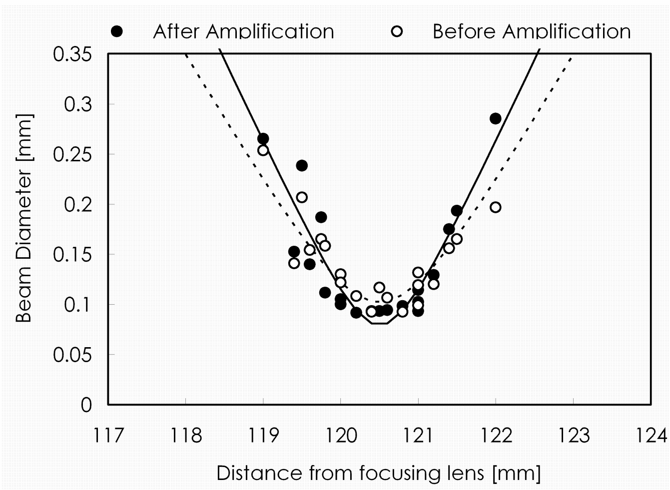

Figure.6 Dependence of focused beam diameter on the distance from the focusing lens

The 1kW, 100kHz, 15ns laser pulse train was employed to irradiate a fast Xe jet of 60m/s speed. Figure 7 shows the plasma behavior under laser irradiation. There was no serious backscattering of the irradiated laser light to the laser amplifier. The jet and plasma were stable during irradiation.

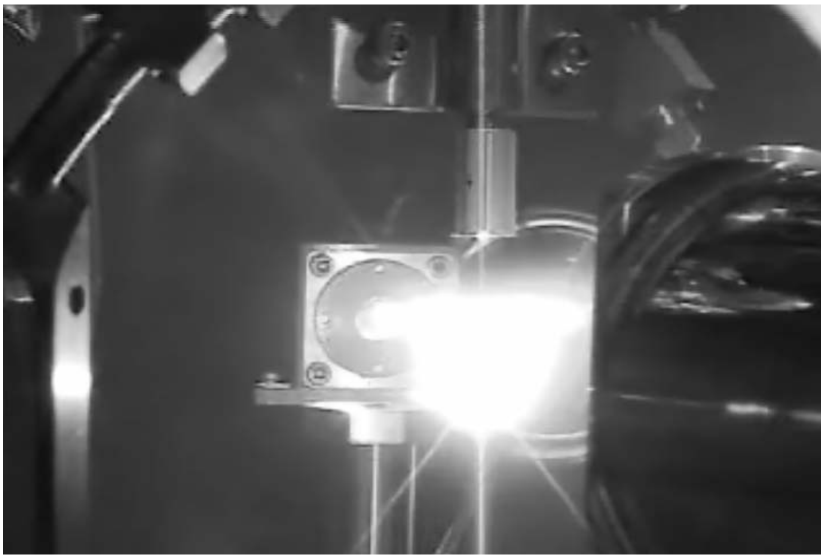

Figure.7 Xenon plasma by 1 kW (repetition rate: 100 kHz, pulse width in FWHM: 15 ns) CO_2 laser irradiation

4. Conclusion and acknowledgement

The development of a short pulse, high average power CO_2 laser is reported on the general concept and its component characteristics. It is anticipated that the present matured CW CO_2 laser technology is well suited for a construction of a pulsed, high repetition rate laser system. A preliminary experiment demonstrated 1 kW in 100 kHz amplification in a small signal gain region. Obtained laser parameters were used to estimate the obtainable power as to be 3 kW with 60 W seed in a saturation region in single line amplification. The laser system is progressing on schedule to demonstrate a viable laser driver for Xenon or Tin droplet targets for 115 W intermediate EUV power.

The reported research was performed under the management of EUVA, a research and developmental program of NEDO.

References

1. T.Sakai and N.Hamada: “ A Q-switched CO_2 laser using intense pulsed RF discharge and high speed rotating chopper”, Proc.SPIE, 2502, 25 (1992)
2. U.Bielesch, M.Budde, M.Fischbach, B.Freisinger, J.H.Schaefer, J.Uhlenbusch, W.Viol: “A Q-switched multikolowatt CO_2 laser system excited by microwaves”, Proc.SPIE, 1810, 57 (1992)
3. H.Tanaka, K.Akinaga, A.Takahashi, and T.Okada: “Emission characteristics of EUV light source by CO_2 laser-produced Xe and Sn plasma”, Proc.SPIE 5374, 737 (2004)
4. T.Higashiguchi, C.Rajyaguru, S.Kubodera, W.Sasaki, N.Yugami, T.Kikuchi, S.Kawata, A.Andreev: Appl.Phys.Lett. 86, 231502 (2005)
5. E.Miura, H.Honda, K.Katsura, E.Takahasi, K.Kondo: Appl.Phys.B70, 1-5 (2000)
6. W.Koechner: Solid State Laser Engineering (Springer Series in Optical Sciences, Springer, Berlin Heidelberg 1996)
7. C.Stolzenberg, J.Speiser, A.Giesen, M.Mikhail: “Power scalability of thin disc lasers in fundamental mode operation” CLEO Europe, CA2-1-Mon, June, Munich (2005)

8. E.S.Shcherbakov: “New achievements in development of superpower industrial fiber lasers and their applications”, CLEO Europe, TFII2-3-WED, June, Munich (2005)
9. G.Goodno, H.Injeyan, H.Komine, S.McNaught, S.Redmond, D.Bell, J.Sollee, J.Serrano, R.Simpson, P.Epp, D.Howland, E.Cheung, P.McGraw, M.Weber, M.McClellan, and W.Long: “Multi-kW near diffraction-limited single frequency Nd:YAG laser” CLEO Europe, CA5-3-THU, June, Munich (2005)
10. M.Nakano, T.Abe and A.Endo: “High average power EUV light source for the next generation lithography by laser produced Xe plasma” ProcSPIE, 5537, 1 (2004)
11. H.Tanaka, K.Akinaga, A.Takahasi, and T.Okada, “Development of EUV light source by CO_2 laser-produced plasma with nano-structured SnO_2 targets”, Proc.SPIE 5374 (2004)
12. Alexander Andreev: Private Communication
13. H.Komori, Y.Ueno, H.Hoshino, H.Ariga,and A.Endo: “EUV characterization of a high power and high-repetition-rate CO_2 laser driven Xe plasma”, SPIE 5018, 149 (2005)
14. T.Miura, A.Endo : “A 100kHz thin-disk Yb:YAG regenerative amplifier” SPIE 6101C-46 (2006)
15. J.W.Witteman: The CO_2 Laser (Springer Series in Optical Sciences, Springer, Berlin Heiderberg 1987)
16. B. J. Feldman: Opt. Commun., 14, 13 (1975)
17. A. Endo, H. Hoshino, T.Ariga and T.Miura: “Development of Short Pulse and High Power CO_2 Laser for EUV Lithograph”, Proc. SPIE 5918, 149 (2005)
18. ISO11146-2:2005,”Lasers and laser-related equipment. Test methods for laser beam widths, divergence angles and beam propagation ratios. General astigmatic beams”