LPP EUV light source employing high power CO_2 laser

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ABSTRACT

We are developing a high power CO_2 laser system for a LPP EUV light source. Recent theoretical and experimental data demonstrate the advantages of the combination of a CO_2 laser with a Sn target including the generation of a high CE and low debris plasma with low energy ions and low out-of-band radiation. Our laser system is a short pulse CO_2 MOPA (Master Oscillator Power Amplifier) system with 22 ns pulse width and multi kW average power at 100 kHz repetition rate. We achieved an average laser power of 8 kW with a single laser beam having very good beam quality. A EUV in-band power of 60 W at the intermediate focus was generated irradiating a rotating tin plate with 6 kW laser power.

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1. INTRODUCTION

Pulsed CO_2 laser systems are very successful tools for various applications ranging from material processing of metals, glass, ceramics and epoxy over paint removal and medical or spectroscopy applications, to the generation of laser produced plasmas as UV, EUV and soft X-ray sources. One drawback is the limited repetition rate for TEA CO_2 lasers, another drawback is the limited controllability of the pulse width for low pressure microwave excited lasers. Attempts were reported a decade ago to operate microwave excited CO_2 laser modules in a Q-switched oscillator mode and an oscillator-amplifier mode [1, 2)]. Typical performances at repetition rate of 4 kHz with output average power of 680 Wand 10 kHz with average power of 800W were pulse energy of 170 mJ, pulse width in full width half maximum (FWHM) of 250 ns, and 70 mJ, 35 ns, respectively. CW output powers were 2 kW and 7 kW, respectively. Laser efficiencies, however, were not very high in both cases in the short pulse mode.

The power requirement of a future EUV light source is $>$ 115 W, 13.5 nm, 2 %bandwidth, at the intermediate focus. This power requirement is enormous. For example, for a CE of 2 % and including the EUV collection efficiency of the LPP system, i.e. only a limited amount of the radiation emitted into 4 pisr can be collected with a EUV mirror, the requirement for the driver laser average power is between 10~30 kW in a ns pulsed mode. This is the most critical issue related to the realization of a LPP EUVL source.

Recent experimental and theoretical work revealed that the wavelength dependence of the conversion efficiency from input laser power to generated EUV in-band power 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 the ns region, or Ti:Sapphire lasers in ps and fs regions [4)]. Some experiments were done by excimer lasers combined with cluster Xenon jets [5)].

Typical rod amplifiers of high average power solid state laser systems are limited by high thermal distortion of the gain medium. This distortion deteriorates the polarization of the laser beam, decreases the laser beam quality thus worsening the laser focus spot size, and damages optical surfaces inside the laser system [6)]. Efforts to overcome the heat distortion are focusing on new laser materials like Yb:YAG and new laser configurations like thin disc or fiber. The development covers the CW regime extending into the multi kW level [7, 8)]. The possibility to operate these thermally less distorted CW lasers in pulsed mode, is limited by the single pulse energy. A large thin slab amplifier is emerging as an alternative high average power amplifier, but bulky laser diodes and the focusing optics are the main cost driver of the laser [9)].

CW CO_2 lasers are the most frequently used lasers in industry due to their comparably low initial and operational costs, as well as their robustness and reliability. And they are environmentally friendly. CO_2 lasers are also operated in long pulsed mode for certain applications. RF-excitation is the most commonly employed scheme in axial flow or conduction cooled slab or waveguide configurations. The design guideline of a multi kW short pulse CO_2 laser system is described in this paper. It main characteristics are high repetition rate, high pulse energy, high amplification efficiency and a high beam quality. The system is based on commercial high average power CO_2 laser modules that are used as amplifiers.

2. HIGH AVERAGE POWER CO_2 LASER FOR LPP EUV LIGTH SOURCE

2.1 CO_2 drive laser system

A CO_2 laser power between 10~30 kW with a pulse width of 15~30 ns is very difficult to realize with a single amplification stage. Therefore we developed a multi stage MOPA (Master Oscillator Power Amplifier) system. Fig. 1 shows the laser system configuration. The system consists of a short pulse high repetition rate oscillator and a multi stage amplifier.

A short pulse oscillator was installed as the seeder for the amplifiers. The laser was an EO Q-switched, 15~30 ns, single P(20) line, RF pumped waveguide CO_2 laser with 60 W output at a repetition rate of 100 kHz. The repetition rate is tunable from 10~140 kHz.

Commercial 5 kW and 15 kW CW CO_2 lasers were installed at our laboratory as amplifiers. Every units are 13.56 MHz RF-excited fast axial flow lasers. Lasers were set-up as amplifiers by replacing all cavity mirrors with ZnSe windows.

The 5 kW laser use a standard gas composition of CO_2:N_2:He=5:29:66 at about 120 Torr gas pressure. The axial gas flow speed is sufficiently high to keep the laser gas temperature inside the operational condition. The length of a single gain region is 15 cm, and 16 cylindrical gain regions are connected in series for one laser unit; the tube inner diameter is 17mm. The total length of the optical pass inside the laser is about 590 cm. The laser operates at 5 kW CW output power with a M^2 =1.8 beam quality. The electrical input power is 36 kW.

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

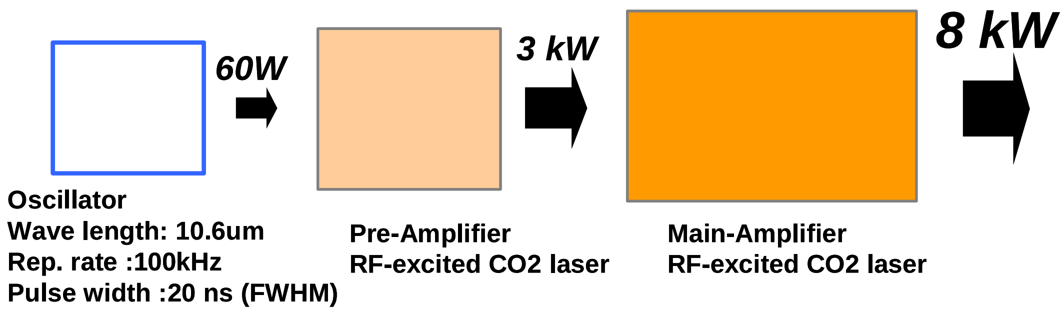

Fig.1 Configuration of the CO_2 MOPA system.

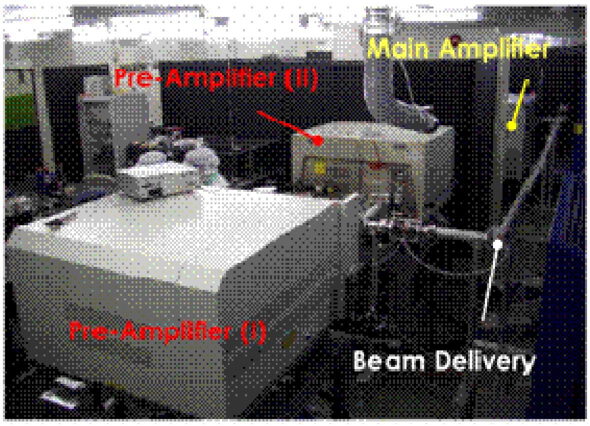

Fig.2.Ovrer view of the CO_2 MOPA system.

2.2 Amplification performance

Fig.3 shows the short pulse MOPA system amplification characteristics. The maximum average output power of 8 kW has been achieved at a repetition rate of 100 kHz as input to main amplifier 3kW. Efficient short pulse amplification with RF-pumped gain modules requires that parasitic oscillations and/or optical coupling between the amplifiers modules do not exist which was experimentally verified. We succeeded to extract 5kW power from 15kW CW amplifier. The extraction efficiency (=(output power-input power)/ CW output power) is over 30%(Fig.4).

This is one of the most important parameters to scale the CO2 drive laser for the commercial LPP EUV light source system **.**

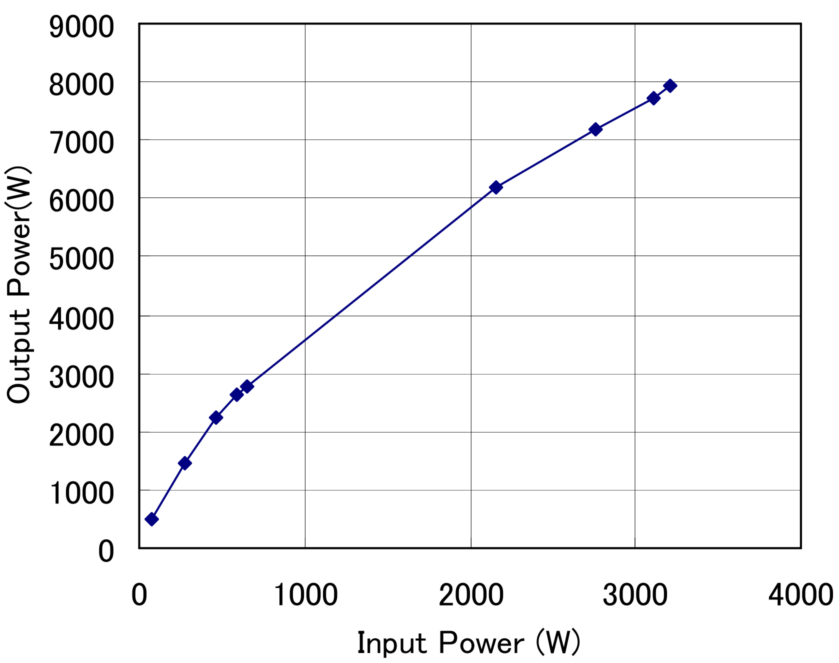

Fig.3 Amplification performance of main amplifier.

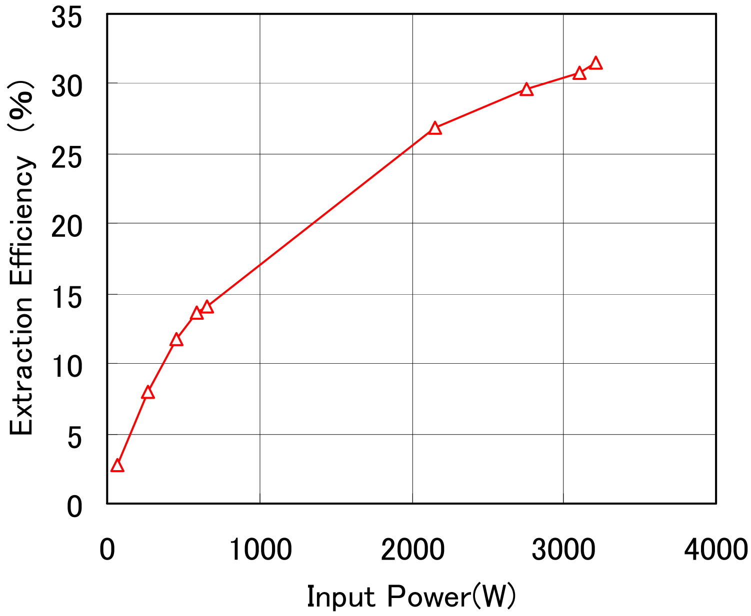

Fig.4 Extraction efficiency of main amplifier.

Filling factor is the level to fill a tube of amplifier with beam diameter. We changed filling factor and measured extraction efficiency at the main amplifier(Fig.5). At that time the average power was restricted about 6kW.Extraction efficiency depends on filling factor. It shows a possibility to extract more power form preamplifiers in this system.

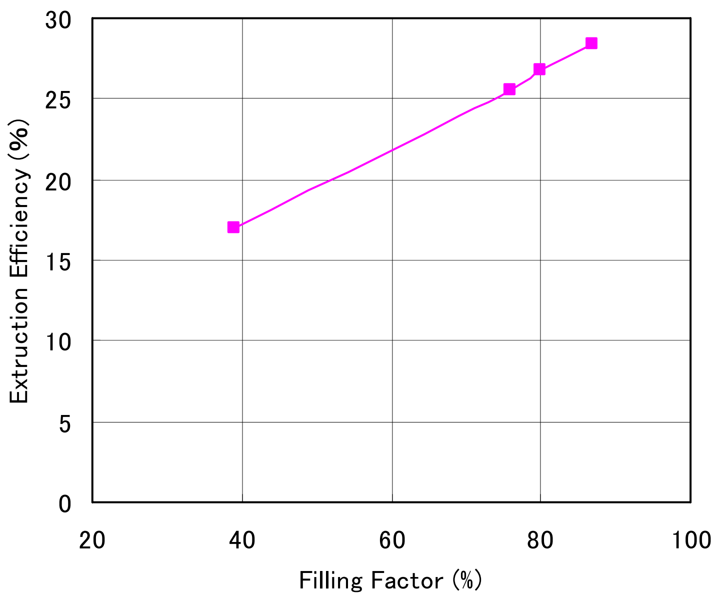

Fig.5 Filling factor dependence of extraction efficiency.

2.3 Beam quality of short pulse amplification

The laser beam quality was measured with a ZnSe lens of 508mm focal length and a slit-scan type beam profiler (Photon Inc., NanoScan). The laser beam size at the lens focus was measured for the oscillator and amplifier, see Fig.6, resulting in a beam propagation factor M^2 of 1.1. Especially, the laser beam size is identical before and after amplification, i.e. the amplification does not cause any phase distortion. Fig7 shows a typical beam profile.

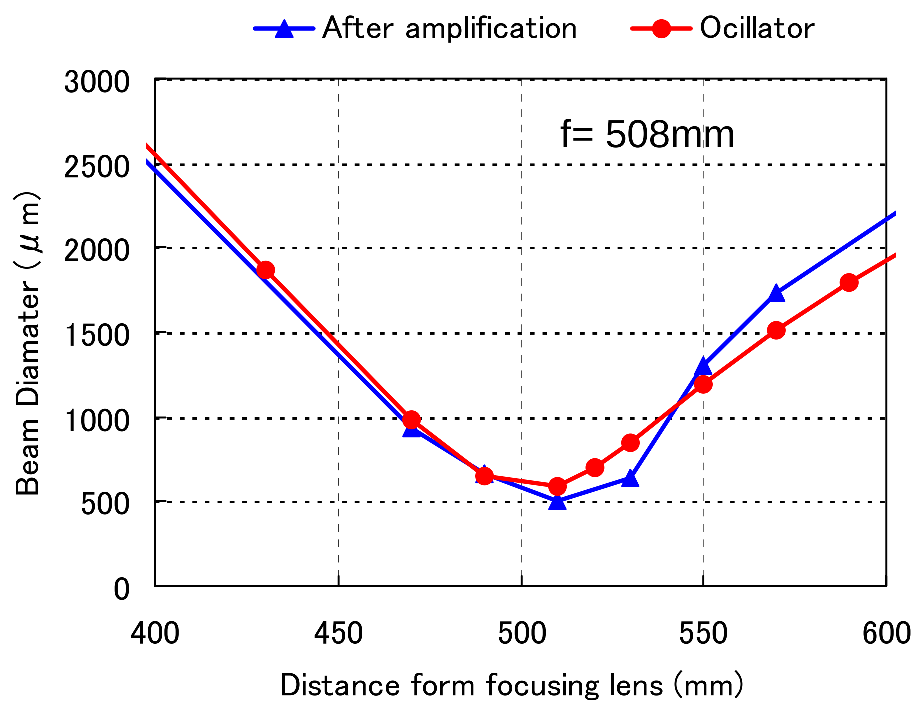

Fig.6. CO_2 laser beam quality.

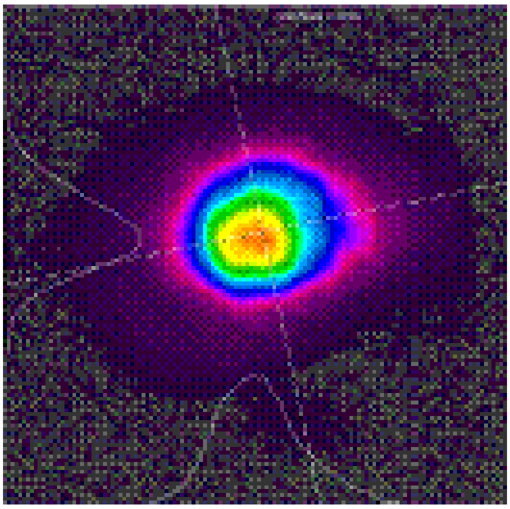

Fig.7.Typical CO2 laser beam profile.

Fig.8 shows the temporal laser pulse profile of the amplified laser output. The pulse duration is 20 ns (FWHM) and the pedestal is below 10% of the total pulse energy. A pedestal and/or tail of the seed laser pulse can be also amplified and reduce the laser gain. There was no incident buck scattering light from Sn target that is harmful for laser system.

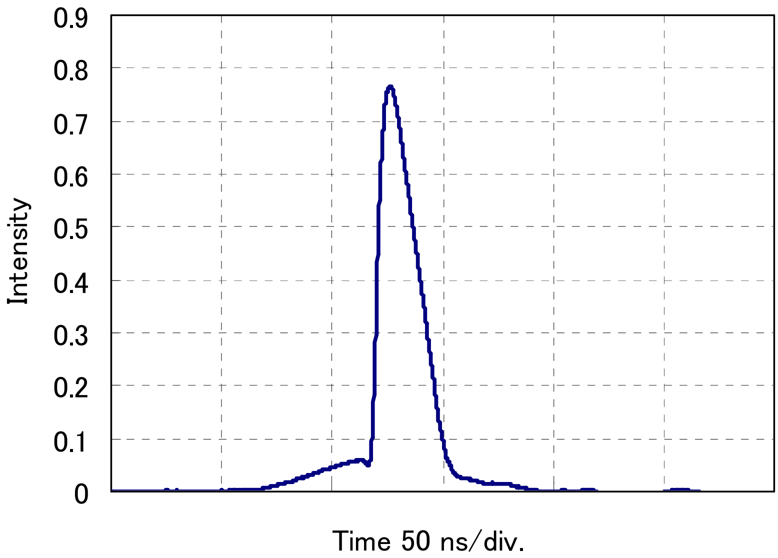

Fig. 8. Temporal laser pulse profile.

2.4 Pulse energy stability

A EUV light source was operated with the high power CO_2 MOPA laser, a preliminary rotating Sn disk target and a collector mirror in order to evaluate the EUV output performance at the intermediate focus. The laser power was 6 kW. The laser beam was focused onto the solid Sn disk at an angle of 45 degree related to the disk surface normal. Fig.9 shows the laser energy stability measured during target irradiation at 100 kHz without any laser stability control: the stability was 2% (3 σ , 500pls). The stability depends on oscillator's energy stability that was not so good. So we can improve the stability of this system to employ good oscillator. The laser system was 20% duty operated, but it has ability to operate at 100% duty.

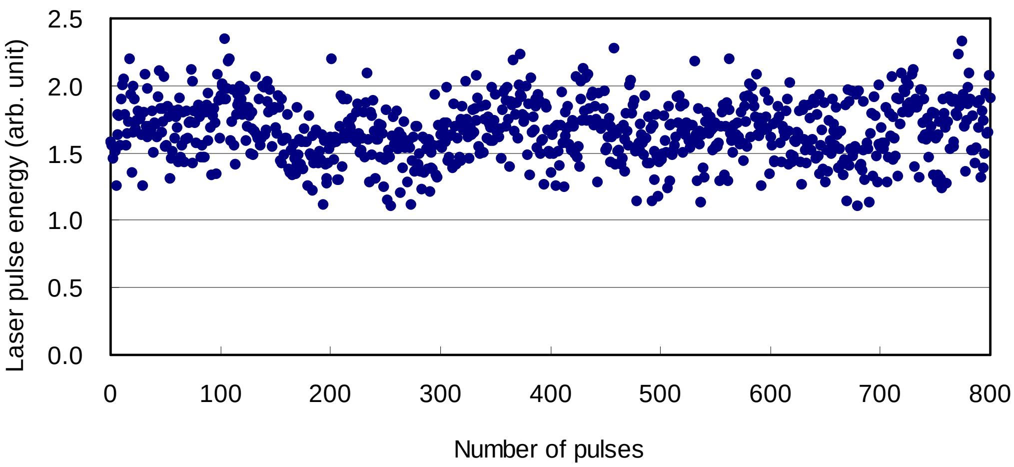

Fig. 9 Laser pulse energy stability; 100kHz CO2.

At the same time the EUV pulse energy was measured with a calibrated photo diode (Fig.10). The EUV energy stability was 3.8%(3 σ ,500pls). The EUV source power was 143W/2 pi, i.e. the average conversion efficiency is about 2.5%.

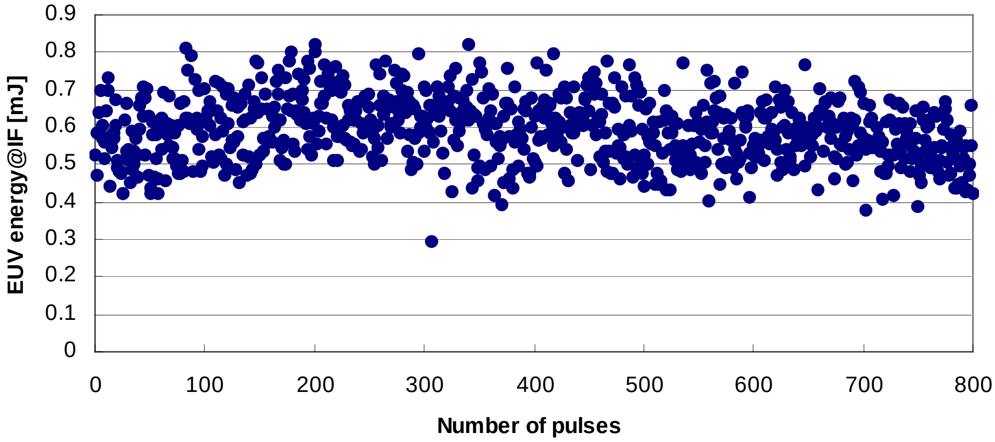

Fig. 10 EUV pulse energy stability; @I.F..

3. CONCLUSION

The development of a short pulse, high average power CO_2 drive laser for a LPP EUV light source has been reported. A laser output power of 8 kW at a repetition rate of 100 kHz was achieved with a single laser beam having very good beam quality. It is emphasized that the present matured CW CO_2 laser technology is well suited for the construction of a pulsed, high repetition rate laser system. Especially, the CO_2 laser based drive laser system enables power scaling. The average EUV output power obtained with a preliminary rotating disk target is 143W/2pi equivalent to 60 W at the intermediate focus.

<Driver Laser Specification>

Laser Power: 8 kW

Pulse Width: 20 ns

Repetition Rate: 100 kHz

Beam quality : M^2 1.1

Stability: 2%(3 σ ,500pls) : (free running)

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