Flexible CO_2 laser system for fundamental research related to an extreme ultraviolet lithography source

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A CO_2 laser system with flexible parameters was developed for fundamental research related to an extreme ultraviolet (EUV) lithography source. The laser is a master oscillator and power amplifier (MOPA) system, consisting of a master oscillator, an externally triggered plasma switch, a preamplifier, a main amplifier, and electronic synchronization units. The laser pulse duration can be varied easily from 10 to 110 ns, with a constant peak power for pulse durations from 25 to 110 ns. The MOPA laser system can also be operated in dual-oscillator mode to produce laser pulse with pulse duration as long as 200ns and a train of laser pulses with flexible interval. The divergence of the laser beam is 1.3 times the diffraction limit. The laser intensity on the target surface can be up to 8×10^{10} W/cm^2. Utilizing this CO_2 MOPA laser system, high conversion efficiency from laser to in-band (2% bandwidth) 13.5 nm EUV emission has been demonstrated over a wide range of laser pulse durations. © *2009 American Institute of Physics.* [doi:10.1063/1.3270257]

I. BACKGROUND

High power pulsed laser-produced plasmas (LPPs) provide compact light sources in soft x-ray and extreme ultraviolet (EUV) regions, especially as the most promising candidate for the illumination light source used in EUV lithography (EUVL).[1] EUVL is an emerging technology for next generation lithography tools used in the semiconductor industry to produce electronic node with feature size of 32 nm or smaller. A powerful, long-lifetime, and low cost EUV source is still one of the most critical challenges in the development of EUVL. Most of the efforts to develop the an EUVL source focus on 13.5 nm EUV emission due to the fact of that multilayer Mo/Si interference mirror with normal-incidence reflectivity of 70% within a 2% bandwidth (in-band) centered at 13.5 nm is the only choice for the optics used in EUVL. The beginning use of EUVL in HVM requires a power of 115 W at intermediate focus and the further improvement of the EUVL to produce smaller feature size will update this requirement to 250 W.

Compared to discharge-pumped plasma EUV source, LPP is more hopeful to be the real light source in HVM due to its higher collection efficiency, isolated plasma from optics, manageable thermal load, and the ability to scale to high power, etc. Various lasers, including ultraviolet excimer lasers,[2] Q-switched Nd:YAG (yttrium aluminum garnet) laser with wavelength of 1.06 μm,[3] newly developed fiber laser,[4] and far infrared CO_2 laser at 10.6 μm (Ref. 5) have been tried to generate efficient EUV emission. Diode-pumped Nd:YAG laser has been considered as the main laser driver for high volume manufacturing (HVM) EUVL source for a long time due to its compact foot print, easy manipulating, and numerous laser facilities accessible for universities and companies. However, in recent time, Nd:YAG laser will hopefully be replaced by CO_2 laser due to its higher in-band conversion efficiency (CE), commercially available high power, lower cost of ownership, and a better credit in high duty industry applications.[6]

However, since the material of interest to EUVL source is Sn (Z=50), the physics dominating the generation and the transport of the in-band 13.5 nm EUV emission in laser-produced Sn plasma has been never understood completely. Especially for CO_2 laser-produced Sn plasma, since most of the previous efforts have mainly focused on Nd:YAG laser-produced Sn plasma and a suitable CO_2 laser system for EUVL source fundamental research is hardly available for universities and academic institutes, there has been little effort on fundamental researches on the interaction of CO_2 laser Sn plasma related to EUVL source.

With a short pulse CO_2 laser system at Brookhaven National Laboratory, it has been shown that CO_2 laser pulse with pulse duration of 25 ns is more efficient to generate in-band 13.5 nm EUV emission as compared to subnanosecond laser pulse.[7] The parameters of the large-scale CO_2 laser system used in industries to demonstrate full power EUVL source are very much fixed.[6,8] The commercially available transversely excited atmosphere (TEA) CO_2 laser has typical pulse duration of 100 ns followed by a microsecond long tail. Laser intensity and pulse duration of a single stage TEA CO_2 laser equipped with a fast switch are very limited. A CO_2 laser with flexible parameters is of importance to further understanding and optimization of the EUVL source based on CO_2 laser-produced plasmas.

In this report, we present efforts to develop a CO_2 master oscillator and power amplifier (MOPA) laser system with

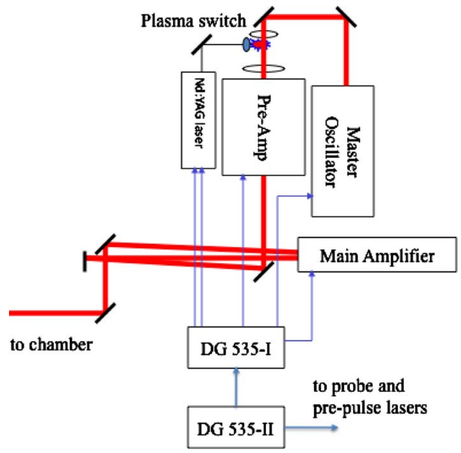

FIG. 1. (Color online) Schematic illustration of the CO_2 MOPA laser system.

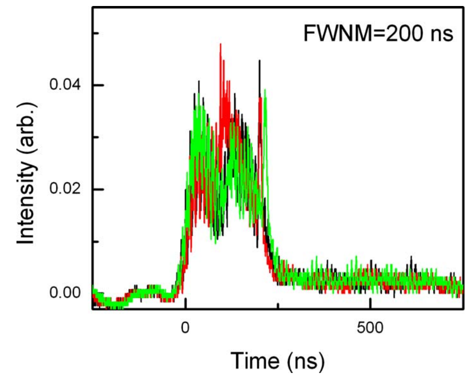

FIG. 2. (Color online) Waveform of CO_2 laser pulse with pulse duration of 200 ns (three shots).

easily adjustable parameters. An externally laser-triggered plasma switch enables flexible laser pulse durations. The power amplifiers ensure laser intensity high enough for an EUVL source. The dual-oscillator arrangement extends its pulse duration. Flexibility and accurate synchronization with prepulse and probe beam make the MOPA system very useful to the EUVL source fundamental research, which requires variable plasma conditions and accurate plasma diagnostics.

II. STRUCTURE OF THE CO_2 MOPA laser system

CO_2 laser transitions occur between low-lying vibrational-rotational levels of the ground electronic state.[9] The energy of the vibrational level is distributed over a manifold of rotational sublevels, giving rise to the possibility of many lasing transitions between two vibrational levels. We will focus on 10.6 μm lasing from the transition of P(20), i.e., rotational states j=19 to j=20, between the first vibrational states of asymmetric (v=3) and symmetric (v=1) stretch modes of the CO_2 molecule. In CO_2 laser medium, N_2 provides an efficient extra channel for the population of v=3 vibration of CO_2. In the presence of CO_2 molecules, the vibration energy of N_2 can be easily transferred to the v=3 vibration of CO_2 due to very small energy gap between the vibration level v=1 of N_2 and the upper level of CO_2. The excited CO_2 molecules oscillate to form a giant laser pulse with typical pulse duration of 100 ns due to laser gain switch. Since N_2 can stay in its excited state for a long time, even after laser pulse due to gain switch (~100 ns) N_2 still transfer energy to the upper level of CO_2 molecules, resulting in a low intensity tail lasting for a couple of microseconds. We will show later that the long low intensity tail cannot contribute to EUV emission efficiently, but produces a number of ions. So the long tail has to be removed.

The CO_2 laser system is a MOPA system. Its schematic illustration is shown in Fig. 1. The laser consists of a master oscillator (MO), an externally triggered plasma switch, a preamplifier, a main amplifier, and synchronization units. The CO_2 laser beam from the MO passes through a telescope consisting of two plano-convex spherical ZnSe lenses with focal lengths of 5 and 7.5 in., respectively. The plasma switch is introduced into the telescope to cut the long tail and to vary the laser pulse duration. After passing the telescope, the time-cut and space-expanded CO_2 laser beam is amplified through single- and double-pass in the pre- and the main amplifiers, respectively. Finally, the CO_2 laser beam is guided into a vacuum chamber for the experiments of laser plasma interaction.

The MO, the pre- and main amplifiers are all TEA CO_2 lasers. The three CO_2 lasers and the Nd:YAG laser (Lumonics HY-400) used to trigger the plasma switch are synchronized with a digital delay/signal generator unit (Stanford DG-535). When necessary, another two Nd:YAG lasers, one is a Q-Switched Nd:YAG laser (Continuum Surelite II) with pulse duration of 7 ns and the other is a Q-Switched Nd:YAG laser equipped with a stimulated Brillion scattering pulse compressor (EKSPLA SL-350, its pulse duration can be down to 130 ps), can also be synchronized with the CO_2 MOPA laser system with another DG 535, as shown in Fig. 1. The two Nd:YAG lasers are used as a prepulse to modify the plasma conditions and a probe beam for plasma diagnostics (such as shadowgraphy and interferometry), respectively. Since a hydrogen thyratron is employed in both the MO and the preamplifier, time jitters among the CO_2 MOPA laser, the prepulse, and the probe beam are better than 5 ns. With this capability, integrated experiment to investigate the fundamental plasma and plume physics dominating the generation and the transport of the EUV emission and ions could be carried out with precise plasma conditions and accurate plasma diagnostics, providing a unique tool to explore the fundamental physics related to the development of an EUVL source.

The MOPA laser system can also be operated in dual-oscillator mode. In this way, the preamplifier is operated as another oscillator. The two beams from the oscillators are amplified in the main amplifier, combined and focused into the same focal spot. The interval between the two laser pulses can be easily varied by adjusting the delay time on the DG 535. Using a F/5 focal lens, the laser intensity on the target is still up to 2×10^{10} W/cm^2, which is high enough for EUVL source research. In this case, the pulse duration can be extended up to 200 ns and a train of CO_2 laser pulses with flexible interval is realized. Typical waveforms of the 200 ns laser pulse and a pulse train with an interval of 0.8 μs are shown in Figs. 2 and 3, respectively. The oscillation structure in the CO_2 laser pulse waveform is due to the

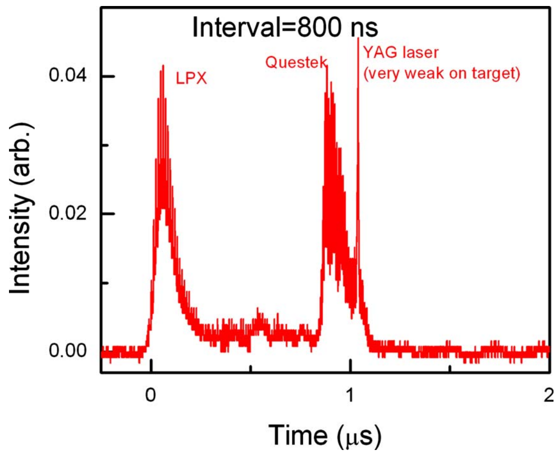

FIG. 3. (Color online) A train of CO_2 laser pulses with an interval of 0.8 μs.

well-known intermode beating. The CO_2 laser pulse waveform is measured with a photoelectromagnetic IR detector (Boston Electronics) and recorded by a digital oscilloscope (Tektronix TDS 5054B-NV).

III. OPTIMIZATION OF THE MASTER OSCILLATOR

The MO is a TEA CO_2 laser converted from a preionized excimer laser (LPX 240 i). The LPX laser is operated with high voltages from 16 to 26 kV. The ratio of the main to peak capacitors is 3.94. Its discharge area is $12\times22\times1150$ mm^3. The laser is equipped with a gas circulation system. And an electrostatic filter is employed to remove debris from the discharge. The cavity is filled with still gas. No significant decay of laser pulse energy was observed within a couple of weeks operated at low repetition rate. The discharge voltage goes up rapidly with increasing gas pressure. In order to get a glow discharge, the pressure of CO_2 laser gas is reduced to be lower than 1 atm, i.e., from 0.7 to 0.8 atm. The low pressure gives more flexibility to optimize the ratio of gas mixture to get a high peak power.

The resonant cavity of the MO consists of a concave (with a 30 m curvature) high reflectivity ZnSe mirror and a parallel-plane ZnSe output coupler with reflectivity from 50% to 80%. The distance between the mirror and the output coupler is 1.7 m. A circular aperture with a diameter of 10 mm is inserted into the cavity, placed at a distance of 25 cm away from the output coupler. The purpose of the aperture in the cavity is to get a circular beam pattern near the target chamber.

The use of an output coupler with a lower reflectivity could help reduce the laser pulse duration and enhance peak power. Typical waveforms of the CO_2 laser from the MO using output couplers with reflectivity of 50% (narrower one) and 80% (broader one) are shown in Fig. 4. The gas mixture ratio is $CO_2:N_2:He=8:10:82\%$. The highest output energy is achieved with this gas mixture ratio. It is seen in Fig. 4 that laser pulse durations are 70 and 110 ns for 50% and 80% reflectivity, respectively. The reason comes from the increased threshold of the laser oscillation with a lower reflectivity, since less light is fed back into the cavity. The weak part of the laser pulse located at the rising and falling

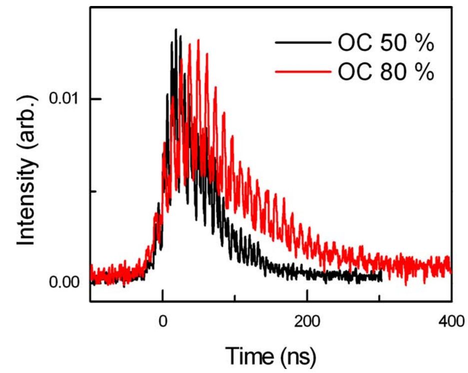

FIG. 4. (Color online) Waveforms of CO_2 laser pulse with output coupler with reflectivity of 50 % (narrower one) and 80 % (broader one).

slope, obtained with a high reflectivity output coupler, cannot get enough gain to sustain the oscillation with a lower reflectivity. So shorter pulse duration results. But since there is still excited N_2, the tail is still there. Smaller laser pulse energy was also observed with a lower reflectivity output coupler.

The gas ratio was optimized to obtain high averaged peak power and to reduce the microsecond tail following the gain switch laser peak. Typical waveforms of CO_2 laser from the MO with two kinds of gas mixture ratios, i.e., $CO_2:N_2:He=8:10:82\%$ (the one with longer tail) and $CO_2:N_2:He=20:4:76\%$, are shown in Fig. 5. It is seen in Fig. 5 that the microsecond tail is significantly reduced in magnitude and time with the later gas mixture ratio. With the optimized gas mixture ratio, output energy is decreased slightly as compared to that of high-energy-output ratio, i.e., from 300 to 200 mJ, but the averaged peak power is increased. The energy drop mainly comes from the reduction of the long tail. We will show later that the short tail may be useful to EUV emission due to its modest drop in CE and modest increase in the generation of ions.

IV. EXTERNALLY TRIGGERED AIR BREAKDOWN PLASMA SWITCH

There have been several techniques used to obtain a short CO_2 laser pulse. The use of electro-optics is the most popular and straightforward method. However, the electro-optics for a CO_2 laser are expensive, small-aperture, and easily damaged. Another method is to use a gas breakdown cell

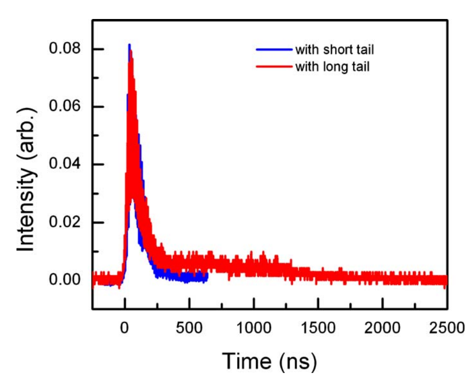

FIG. 5. (Color online) Waveforms of CO_2 laser pulse with gas ratios of $CO_2:N_2:He=8:10:82\%$ (the one with longer tail) and $CO_2:N_2:He=20:4:76\%$.

followed by a linear absorber cell, in this way 30 ps CO_2 laser pulse can be generated.[10] A plasma shutter is an easy and cheap way to cut the unnecessary microsecond tail and to get short pulse duration of CO_2 laser pulse. However, self-induced air breakdown plasma switch, including that assisted with a pinhole, is limited in the application of the EUVL source with the limited pulse duration range and the lifetime of the pinhole.[11] An externally triggered air breakdown plasma switch was developed and integrated into the MOPA system.

Laser-induced air breakdown starts with free electrons generated from multiphoton ionization process. The possibility of multiphoton ionization strongly depends on laser intensity. If there is no initial free electrons, such as dry air in our clean laboratory, high laser intensity is necessary,[12] i.e., $\sim 3\times 10^9$ W/cm^2. Once there are free electrons, laser energy can be efficiently absorbed by the electrons. The electrons are accelerated to high energy. The collisions between the energetic electrons and the molecules could generate more secondary electrons via an avalanche processes. Finally, the air is ionized and heated to hot and dense plasma. Air breakdown plasma is opaque to CO_2 laser light and can act as a switch.

Our experimental arrangement is shown in Fig. 1. The basic idea is to control the laser pulse energy from the MO to keep the laser intensity at the focus of the 5-in.-ZnSe lens used in the telescope below the threshold of laser-induced air breakdown, i.e., $\sim 3\times 10^9$ W/cm^2. In this way, only with the CO_2 laser itself there is no air breakdown plasma, the laser just passes the telescope freely. At a specific time with respect to the CO_2 laser pulse, a 1.06 μm laser from the Lumonics Nd:YAG laser is focused near the focus of the CO_2 laser by a F/5 lens. The Nd:YAG laser generates a small air breakdown plasma. Then the free electrons from the small plasma propagate to the focus of the CO_2 laser beam. The free electrons efficiently absorb the CO_2 laser pulse energy and big air breakdown plasma induced by the CO_2 laser is formed. So the CO_2 laser induced air breakdown plasma is triggered by the Nd:YAG laser and pumped by the CO_2 laser itself.

The CO_2 laser pulse is cut with the big plasma at a specific time. This specific time can be varied by changing the delay time between the Nd:YAG laser and the MO. Thus the pulse duration of the transmitted CO_2 laser can be varied. Typical waveforms of the transmitted CO_2 laser pulse with various pulse durations are shown in Fig. 6. The gas mixture ratio is CO_2:N_2:He=20:4:76%. It is seen in Fig. 6 that pulse durations from 10 to 110 ns can be obtained. It is also worth noting that the peak power of the CO_2 laser pulse with pulse durations from 25 to 110 ns is almost constant. Another notable feather of the cut CO_2 laser pulse is its fast falling slope, with a falling time of ~ 5 ns. This shows that the time for the plasma switch to completely shut down is several ns. The intensity contrast of the plasma switch was found to be better than 500.

In order to further verify the shutdown performance of the plasma shutter, its transmission was observed at various delay times. Typical results are shown in Fig. 7. The optimized gas ratio is employed. It is seen in Fig. 7 that there are two distinct regions on the curve: one is the steeper one from 1240 to 1420 ns, where the transmission increases fast with the delay time; and the other is the linear slower increasing from 1420 to 2200 ns. The fast region corresponds to the cut of the laser pulse, which occupy most of the total pulse energy. The slower region represents the cut of the short tail. It is seen in Fig. 7 that the turning point is located at 0.7. This means that the short tail occupies $\sim 30\%$ of the total pulse energy.

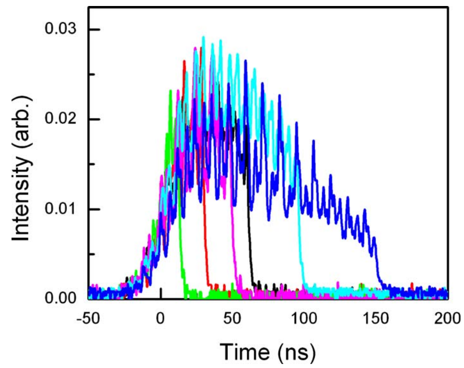

FIG. 6. (Color online) Waveforms of CO_2 laser pulse with various pulse durations cut with the externally triggered plasma switch.

The threshold of CO_2 laser induced air breakdown with the external trigger was investigated by varying the CO_2 laser pulse energy. It was noted that an air breakdown plasma can still be triggered when the CO_2 laser has pulse energy as low as 20 mJ, the corresponding laser intensity is $\sim 1 \times 10^8$ W/cm^2. In our experiments, it was noted that even the shorter tail itself obtained with the optimized gas mixture ratio could be cut without loss of any of the laser pulse.

V. AMPLIFICATIONS

The preamplifier is a TEA CO_2 laser converted from a preionized discharge-pumped excimer (Questek 2560) with operation high voltage up to 32 kV. The Questek laser has a discharge area of $14\times 23\times 760$ mm^3. Its ratio of peak to main capacitors was modified from 1.3 to 2.6 to generate a glow discharge in a high pressure. Still gas is filled in the preamplifier with a gas mixture ratio of CO_2:N_2:He

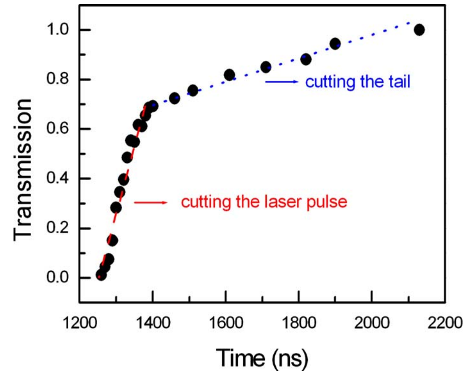

FIG. 7. (Color online) Transmission of air breakdown plasma induced by CO_2 laser as a function of delay times.

=20:4:76%. The Questek laser employs a hydrogen thyratron as the high voltage switch, and its jitter is better than 5 ns.

The main amplifier is a TEA CO_2 laser (Lumonics LaserMark 30) with discharge area of $35\times35\times750\ \text{mm}^3$ and a high voltage up to 35 kV. The gas ratio is fixed at $CO_2:N_2:He=8:10:82\%$. The main amplifier uses a flowing gas. Since the high voltage switch is an air spark, the time jitter is around several 100 ns. However, since the lifetime of the excited CO_2 molecule is several microseconds, the gain does not change significantly with a jitter as long as 2 μs.

The cut CO_2 laser beam from the MO is amplified by passing once and twice through the pre- and the main amplifiers, respectively. When the high voltages of the pre- and the main amplifiers are 32 and 34 kV, respectively, a $6\times$ gain is achieved. Laser pulse energies of 60, 150, 400, and 550 mJ are obtained for the pulse durations of 10, 25, 60, and 110 ns, respectively. In order to check if the CO_2 amplifiers are saturated, the outputs from the main amplifier were measured as a function of various input laser energy densities from 40 mJ/cm^2 to 200 mJ/cm^2. It was noted that amplification is almost linear with various input energy densities, i.e., the gain is almost constant at 6 times. It is known that saturated amplification is required to efficiently extract energy from the amplifier. Since the main amplifier has a large active area, it is possible to get a higher output with more passes through the amplifiers. Double-pass through the preamplifier and triple-pass through the main amplifier is feasible with the present experimental arrangement. However, since the linear amplification is uniform to any spatial and temporal parts with different intensities of the input laser beam, it is good to avoid the distortions to the input laser pulse induced during the amplification. This means that good beam qualities of the input beam, such as spatial intensity, phase distribution, and temporal shape, can be maintained through the amplifiers. No significant change of the input beam qualities was observed after amplification.

VI. PERFORMANCE OF THE MOPA SYSTEM

The CO_2 laser is guided into a vacuum chamber with a ZnSe window. Before entering into the chamber, a small part (2%) of the CO_2 laser pulse energy split with a ZnSe plate with anti-reflection coatings on both sides is used to monitor laser pulse energy (calorimeter is Ophir 3A-SH) and pulse shape for each shot.

The profiles of the laser beam in near and far field are observed with an IR camera (Ophir-Spiricon Pyrocam III). The near field pattern is measured at a distance of 5 m from the exit of the oscillator. The far field pattern is measured with a focusing ZnSe lens with focal length of 7.5 in. The focus of the CO_2 laser is relayed to the camera with a ZnSe lens with a focal length of 5 in. with a $9\times$ magnification. A typical near field beam profile is shown in Fig. 8. It is seen in Fig. 8 that the near field profile is close to Gaussian with slight modifications arising from the aperture placed in the MO. The image of the focal spot and its profile along the central horizontal line are shown in Fig. 9. The diameter (1/e of the maximum magnitude) of the focal spot is 200 μm, as

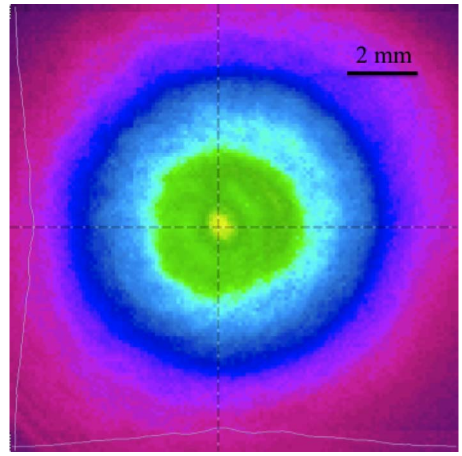

FIG. 8. (Color online) Near field beam pattern of the CO_2 laser.

shown in Fig. 9. The divergence of the laser beam is 1.3 times the diffraction limit. With a F/5 focusing lens, the focal spot diameter can be as small as 100 μm. Laser intensity on the target can be up to $8\times10^{10}\ \text{W/cm}^2$ for the pulse durations from 25 to 100 ns. The intensities for the laser pulse with pulse durations of 10 and 200 ns can be up to $2\times10^{10}\ \text{W/cm}^2$. The laser can be operated up to 10 Hz.

In order to investigate the influence of the short and long tails on the EUV and ions generation from the Sn plasma, in-band CE and time of flight (TOF) of ions from Sn plasmas irradiated with clean CO_2 laser pulse, CO_2 laser pulse followed by the shorter tail, and CO_2 laser pulse with the long tail were observed. It was found that in-band CEs for the clean pulse, the short tail, and the long tail, are 2.6%–3%, 2.1%, and 1.2%, respectively. It is noted that the long tail cannot efficiently contribute to the generation of the EUV emission at all. TOF of ions from the Sn plasma irradiated with a clean CO_2 laser pulse (with lowest magnitude of slow ions), with the short tail (with middle magnitude of slow ions), and with the long tail (with highest magnitude of slow ionswin 0) are shown in Fig. 10. The TOF is observed with a Faraday cup placed at a distance of 15 cm from the plasma. It is seen in Fig. 10 that the ions generated from the short tail are slightly more than the clean pulse due to its additional energy. However, many more slow ions are generated from

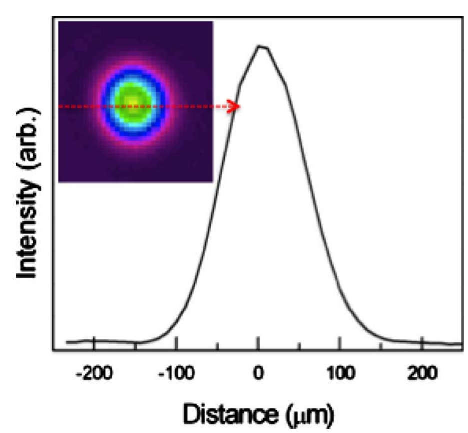

FIG. 9. (Color online) The photo of the focal spot of the CO_2 laser with a 7.5 in. and its intensity profile.

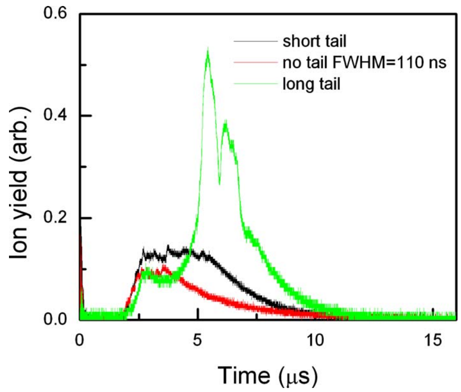

FIG. 10. (Color online) TOF of the ions from Sn target irradiated with a CO_2 laser pulse with long tail (with highest magnitude of flow ions), short tail (with middle magnitude of slow ions), and no tail (with lowest magnitude of slow ions).

the case of the long tail. A clean pulse is necessary to achieve a high in-band CE. A CO_2 laser pulse with a short tail can generate an acceptable in-band CE and ions. The long tail cannot contribute to EUV emission, but generates much more debris.

Utilizing this CO_2 MOPA laser, experiments to generate in-band 13.5 nm EUV emission have been carried out.[13] It has been shown that a high in-band CE, i.e., 2.6%–3%, can be obtained with the CO_2 laser with pulse durations from 25 to 110 ns. Important contributions to the development of an EUVL source have been making with this flexible CO_2 laser.

VII. SUMMARY

A CO_2 MOPA laser system with flexible parameters of interest to the fundamental research for an EUV source was developed. An externally triggered plasma shutter enables easy variation of the laser pulse duration from 10 to 110 ns. Dual-oscillator mode extends the laser pulse duration to 200 ns and makes it possible to explore a novel irradiation method with a pulse train. Laser intensity on the target can be up to 2×10^{10} W/cm^2 over a wide range of laser pulse durations from 10 to 200 ns. The accurate synchronization capability of the MOPA laser with the prepulse and the probe beam makes it useful for fundamental plasma research for an EUVL source.

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