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# Increasing EUV source efficiency via recycling of radiation power

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## ABSTRACT

EUV source power is critical for advanced lithography, for achieving economical throughput performance and also for minimizing stochastic patterning effects. Power conversion efficiency can be increased by recycling plasma-scattered laser radiation and other out-of-band radiation back to the plasma via retroreflective optics. Radiation both within and outside of the collector light path can potentially be recycled. For recycling within the collector path, the system uses a diffractive collection mirror that concomitantly filters all laser and out-of-band radiation out of the EUV output. In this paper we review the optical design concept for power recycling and present preliminary plasma-physics simulation results showing a potential gain of 60% in EUV conversion efficiency.

**Keywords:** EUV, Laser produced plasma, conversion efficiency, diffractive optics

## 1. INTRODUCTION

Source power has long been a challenge for extreme ultraviolet (EUV) lithography using laser-produced plasma (LPP) sources. The near-term requirement, 250W at intermediate focus (IF) within a 2% wavelength band centered at 13.5 nm, has recently been attained [1], but in the longer term 500W or higher will be required to maintain throughput productivity and to minimize the impact of photon shot noise in the lithographic printing process [2]-[4].

In addition to strategies currently being pursued to increase LPP source power (e.g. boosting the $CO_2$ drive laser power), significant gains might be achieved through "power recycling", i.e. returning unused out-of-band (OoB) radiation to the plasma via retroreflective optics [5]-[7]. For recycling of radiation within the collector light path, the system uses an unconventional diffractive collection mirror, which effectively operates the LPP source as an EUV monochromator, eliminating all OoB radiation in the EUV output.

In this paper we review the optical design concept for power recycling and summarize preliminary plasma simulation results showing a potential 60% gain in EUV conversion efficiency for a dual-pulse system [8]. These results are, at this stage, based on simplistic assumptions, which will need to be refined to realistically ascertain the potential of power recycling. Some of the key issues that will need to be addressed in future work are discussed.

## 2. POWER-RECYCLING OPTICS

Plasma-generated and scattered radiation that does not intercept the collector could be directed back to the plasma by spherical, retroreflective mirrors. However, a single spherical reflector would form an inverted image of the plasma on itself, resulting in EUV power fluctuations due to plasma positional instabilities or mirror alignment errors. This limitation can be overcome by using a "relay imaging" method in which the plasma is focused onto an intermediate image, which is then focused onto the plasma by a second mirror reflection; see Figure 1. The double-reflection plasma self-image is non-inverted, so it automatically tracks plasma positional variations and inhomogeneities, and compensates for imperfect mirror alignment. (The image tracking is illustrated by the dashed arrows in Figure 1.)

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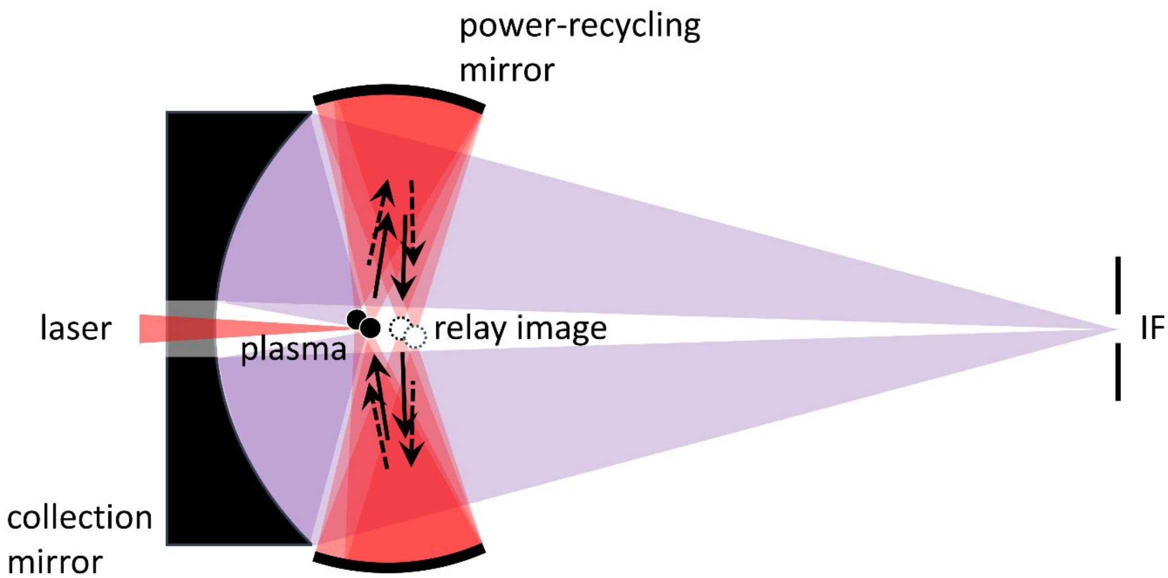



Figure 1. Power recycling via relay imaging to form a non-inverted plasma self-image

For radiation that is directed away from the collector (along a line intercepting the collector), corner-cube retroreflectors can be used to form a non-inverted plasma self-image, as illustrated in Figure 2. Each corner cube is a three-surface pyramidal reflector, with slightly curved surfaces for operation at finite conjugate [9], as illustrated in Figure 3.

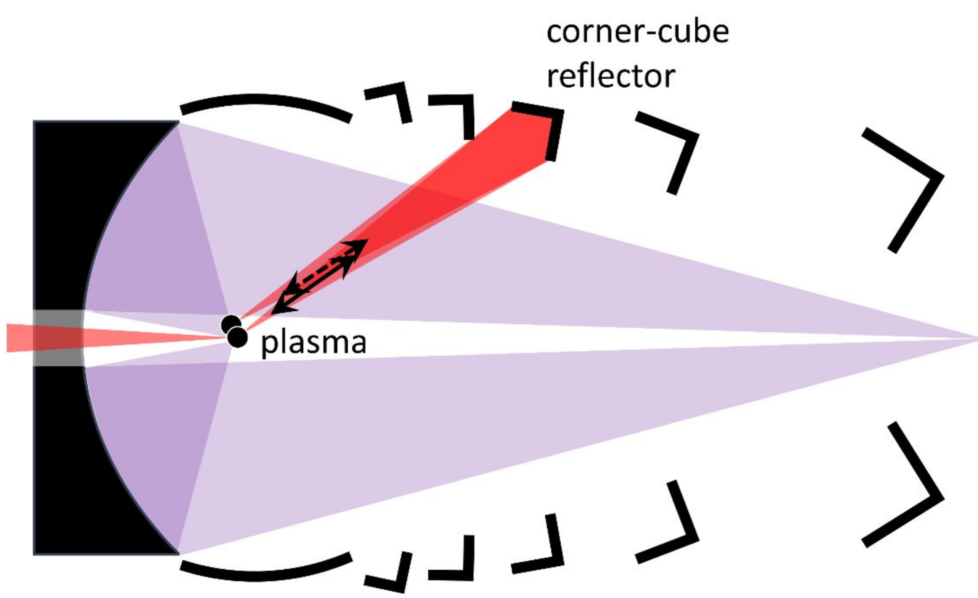



Figure 2. Power recycling using corner-cube reflectors to form a non-inverted plasma self-image

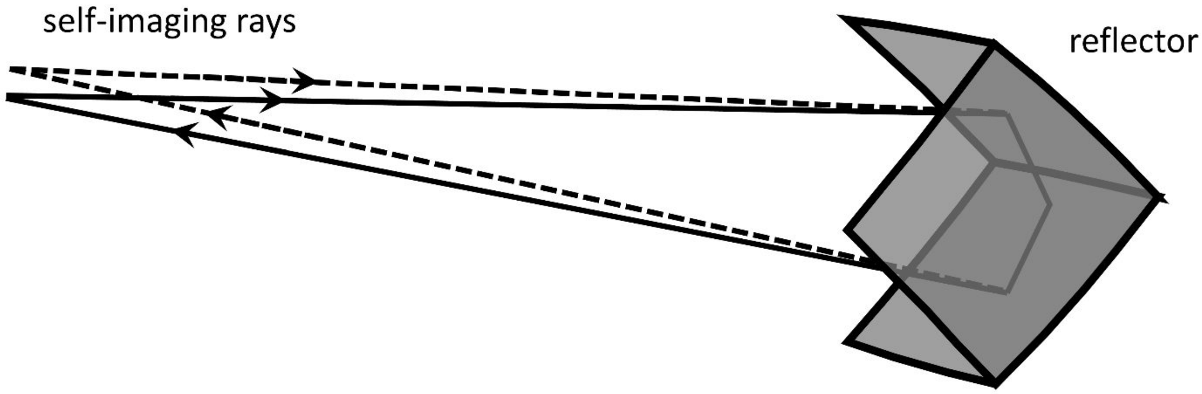



Figure 3. Corner-cube reflector with three curved surfaces for finite-conjugate operation

Much of the OoB radiation intercepting the collection mirror can also be recycled. The system uses an unconventional diffractive mirror, which achieves 100% OoB suppression by, in effect, operating the EUV source as a grating monochromator. A conventional spectral-filtering mirror is ellipsoidal and images the plasma onto the IF. A diffraction grating on the mirror scatters long-wave infrared radiation outside of the IF, while the EUV is collected in the zero order [10]-[14]. With the monochromator design, the mirror is formed to focus the plasma onto a ring or halo surrounding the IF, and a blazed grating on the mirror selectively diffracts EUV into the IF. All OoB radiation is either undiffracted (i.e., concentrated in the zero-order ring), or is excluded from the IF via chromatic dispersion; see Figure 4. (A conventional collection mirror cannot take advantage of chromatic dispersion to effect spectral filtering because there is no dispersion in the zero order.)

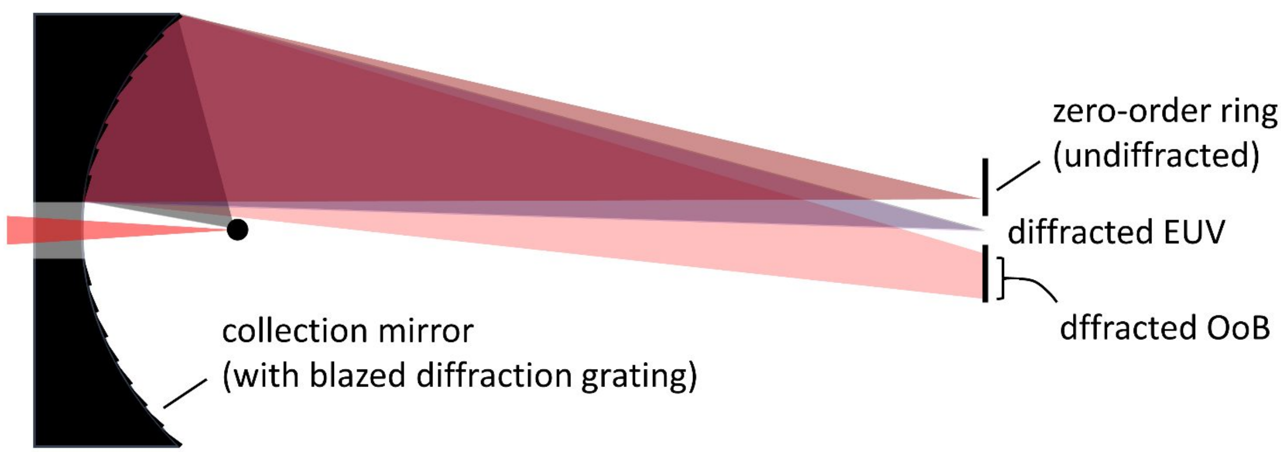



Figure 4. EUV monochromator using a blazed grating on the collector

Figure 5 illustrates a typical blazed EUV grating geometry in cross-section. The grating is patterned in the EUV mirror substrate and has a sawtooth profile, with a typical period of less than $10\,\mu\mathrm{m}$ and depth of less than $10\,\mathrm{nm}$. (The aspect ratio is of order 1000:1, comparable to the ratio of the collection mirror focal length to the plasma diameter.) A conventional EUV reflective coating (e.g. a Mo/Si multilayer stack, 50 bilayers, $7\,\mathrm{nm}$ depth per bilayer) is conformally deposited on the grating. This type of “conformal-multlayer” grating represents one of several design options. Other possible grating structures discussed in [6] include high-order blazed gratings and “patterned-multilayer” gratings (in which the grating is patterned in the multilayer stack, not in the substrate).

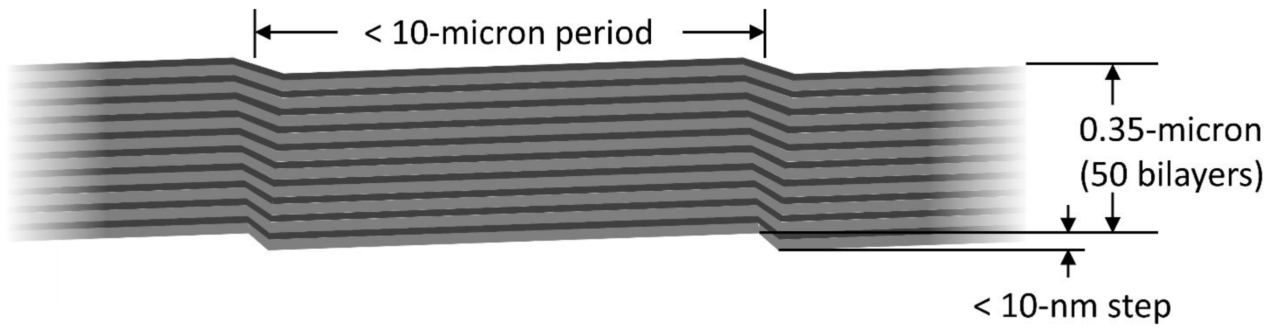



Figure 5. Conformal-multilayer EUV blazed grating

The monochromator design can be adapted for power recycling by expanding the zero-order beam with an axicon mirror and retroreflecting the beam with corner-cube mirrors; Figure 6. Most of the OoB is concentrated in the zero-order ring focus for wavelengths much larger than 13.5 nm, so the optical loss from grating diffraction will be minimal. However, recycling efficiency will be limited by the mirror reflection efficiencies. Figure 7 illustrates single-surface, normal-incidence reflectance spectra for several mirror types: an enhanced-aluminum mirror (100 nm $MgF_2$ on Al), a bare molybdenum mirror (which might be used for the axicon), and a blazed, conformal-multilayer EUV grating with 50 Mo/Si bilayers (the collector). Significant efforts in coating design may be required to overcome the low reflection efficiency at short wavelengths in the collector path.

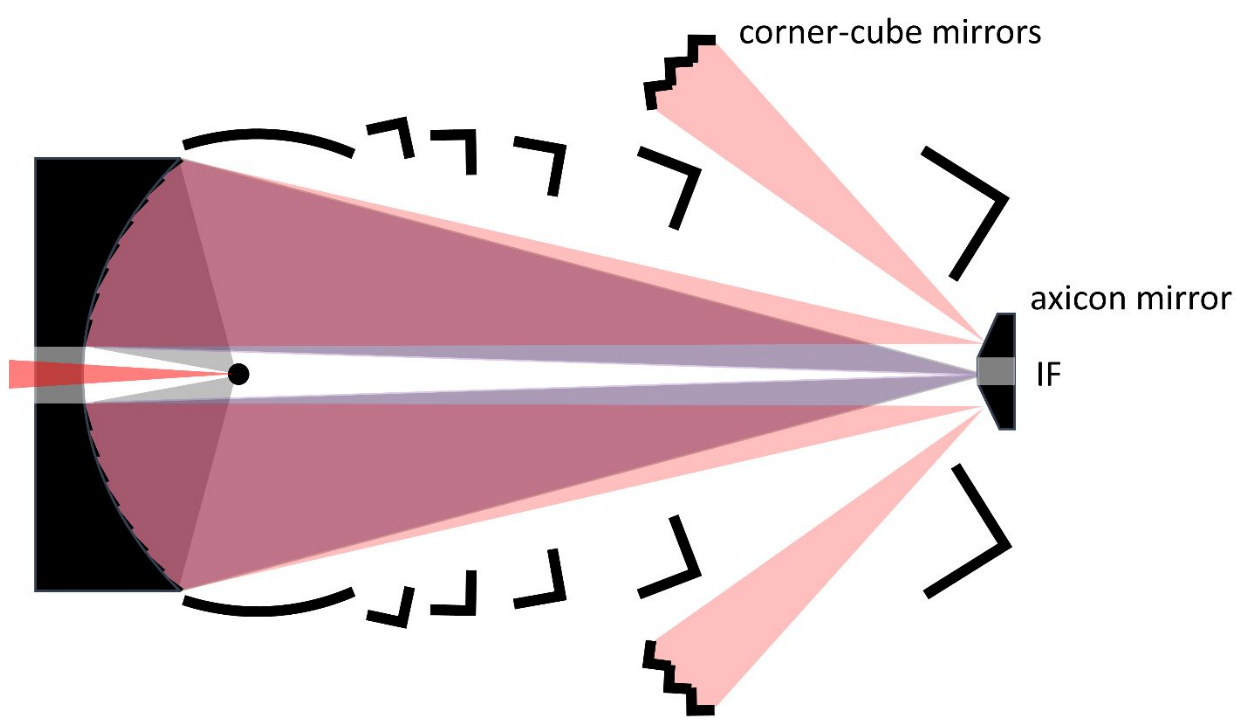



Figure 6. EUV monochromator with power recycling in the collector light path

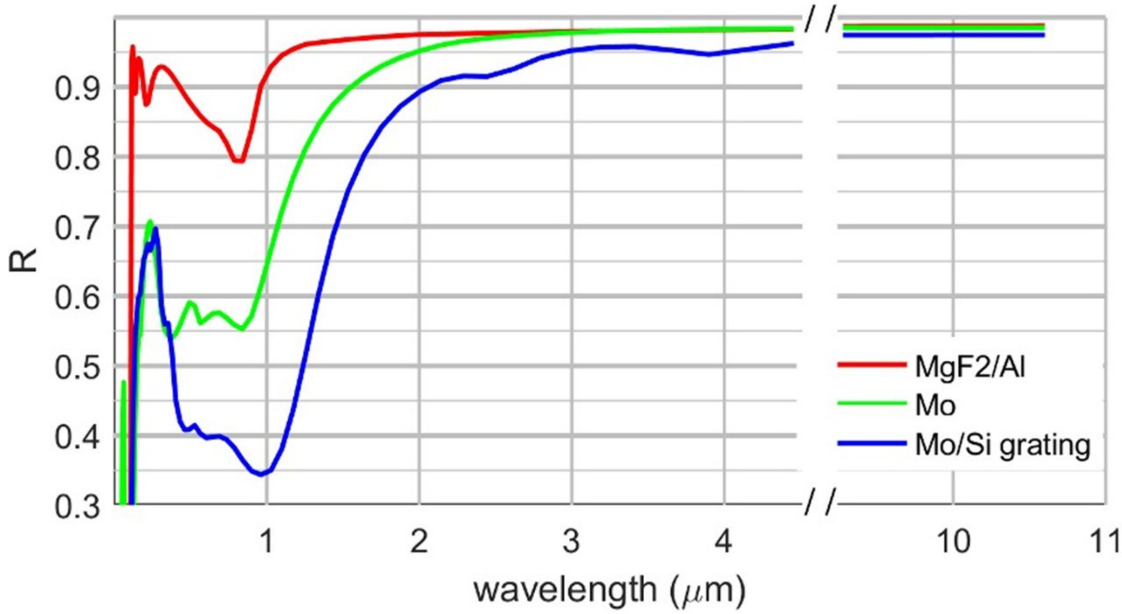



Figure 7. Reflectance spectra (single-surface, normal incidence) of several reflector types

## 3. PLASMA-PHYSICS MODELING

Preliminary plasma physics simulations of LPP power recycling have been conducted using the HEIGHTS computer simulation package (High Energy Interaction with General Heterogeneous Target Systems) developed at Purdue CMUXE (Center for Materials Under eXtreme Environments) [15]-[19]. The methodologies, simulation scenarios, and results are detailed in [8]. Results for one scenario, a dual-pulse system, are summarized below.

We simulated a baseline system using a pre-pulse laser with wavelength $0.266\,\mu\text{m}$ and energy $10\,\text{mJ}$, which provided a laser intensity of $2.5\times10^{10}\ \text{W/cm}^2$ on a tin droplet target with radius $25\,\mu\text{m}$. The pre-pulse duration was $20\,\text{ns}$, and the delay between the pre-pulse and the $CO_2$ drive-laser pulse was $500\,\text{ns}$. The main pulse had a pulse duration of $30\,\text{ns}$ and laser intensity of $5\times10^{9}\ \text{W/cm}^2$, distributed over a focus spot of radius $250\,\mu\text{m}$. The pre-pulse allowed efficient $CO_2$ laser coupling to the expanded plasma cloud following the delay time.

The calculated EUV conversion efficiency (CE) in this case was 3.0% without recycling. The CE can be higher with more optimization of the dual laser parameters and target conditions. Simulations with recycling initially showed a decrease in CE, apparently due to overheating and over-expansion of the vapor/plasma cloud prior to the main $CO_2$ laser pulse. This problem could be avoided by reducing the pre-pulse energy and/or delay time to achieve an optimum plasma with recycling. But to evaluate the effect of recycling on the plasma evolution during the main $CO_2$ laser pulse, we ran additional simulations with recycling activated only after the pre-pulse delay time (under the premise that the pre-pulse conditions could be re-optimized, with recycling, to produce an expanded target in substantially the same initial condition for the main pulse).

For the recycling case, we assumed recycling of scattered/emitted radiation with an axial range of 10° to 170° from the laser axis, with a compound mirror reflection efficiency of 90% over the full OoB spectral range including the $10.6\text{-}\mu\text{m}$ laser wavelength. (The 90% efficiency is probably overly optimistic for the collector light path, but overly conservative for recycling outside of the collector path.) Under these conditions the simulated CE increase to 4.8% relative to the baseline 3.0% CE with no recycling (a 60% gain).

Figure 8 shows the EUV plasma formation (temperature distribution) without recycling (left panel) and with recycling of all the radiation (right panel) during the main pulse of dual-beam system. While approximately the same maximum electron temperatures were achieved in both cases, much larger heated volume with higher EUV emission area was created due to absorption of recycled plasma radiation.

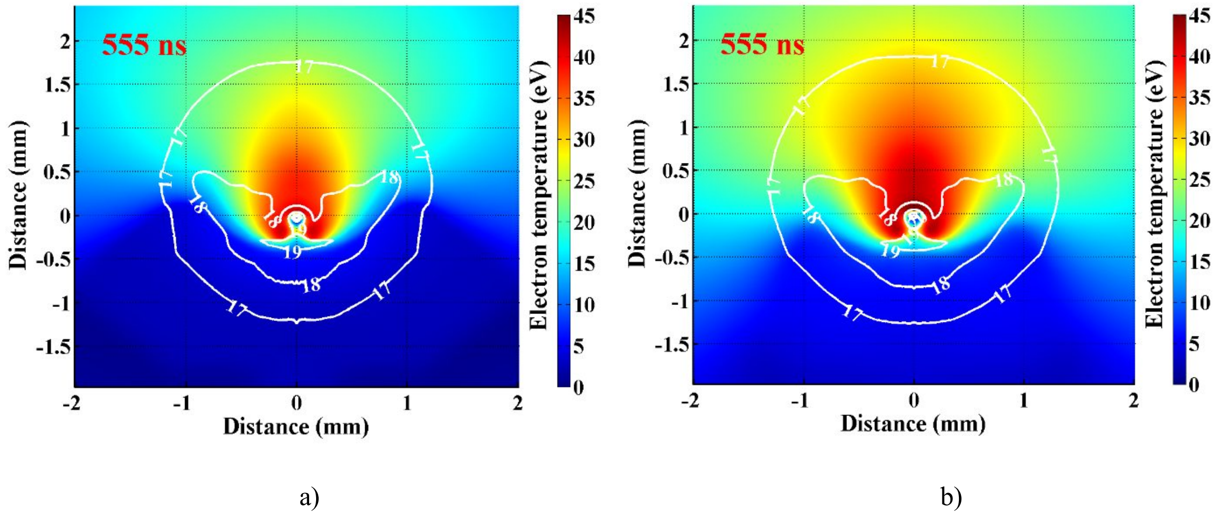



Figure 8. Electron temperature and density (white contours labeled by logarithmic values) distribution in plasmas created by the main, $CO_2$ laser: a) without recycling; b) with recycling of laser and plasma radiation

Figure 9 shows the corresponding in-band emission irradiance of the EUV source for the two cases. The figure also illustrates the range of temperatures appropriate for the EUV emission in the Sn plasma produced by the dual-beam technique (shown by grey contours).

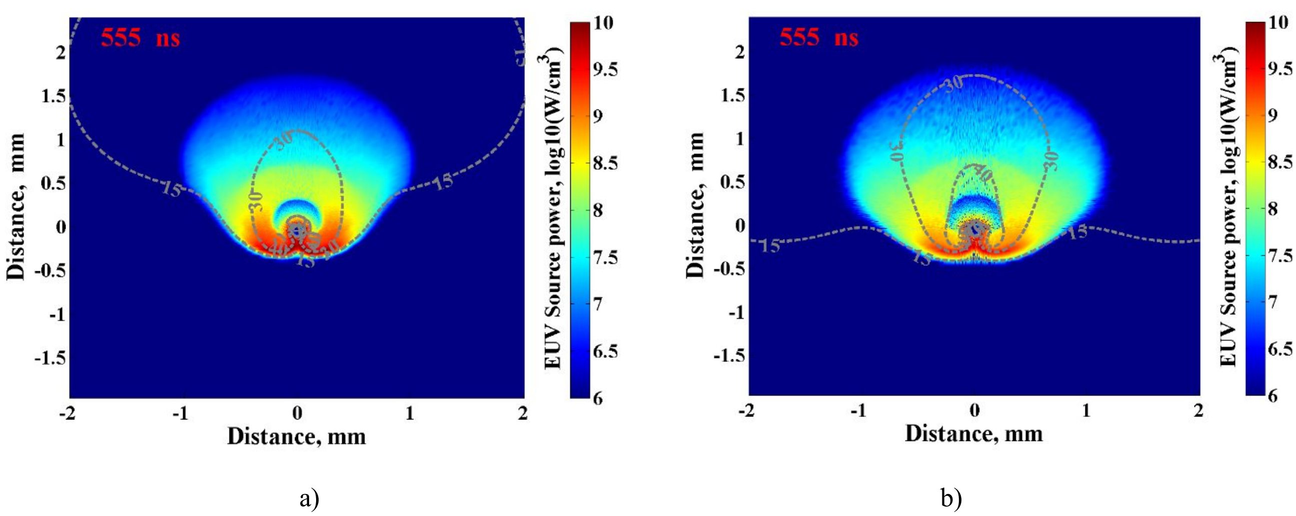
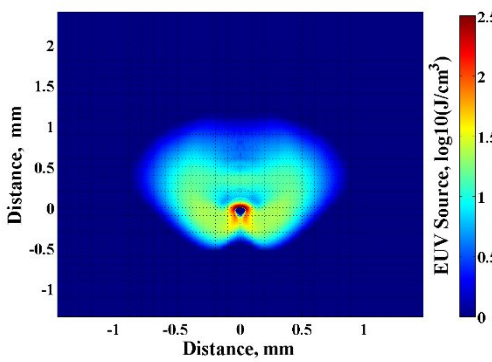


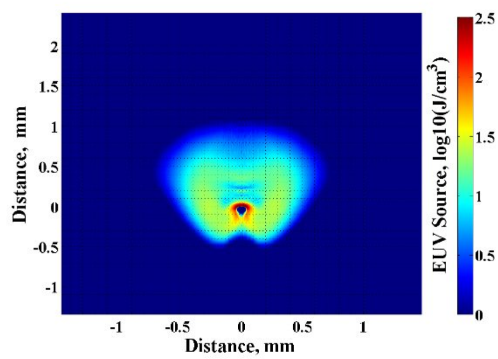

Figure 9. Temporal EUV sources at 35 ns after beginning of main laser pulse (30 ns FWHM): a) without recycling; b) with recycling of laser and plasma radiation. Grey contours show temperature distribution.

We also performed simulations with recycling of only the 10.6-μm $CO_2$ laser wavelength (90% recycling efficiency at 10.6 μm, zero at all other OoB wavelengths). In this case, the CE gain was insignificant (it only increased from 3.0% to 3.1%). The simulation showed no significant benefit to recycling the laser wavelength, apparently because the expanded target absorbs almost all of the 10.6-μm radiation. This observation will need to be confirmed and corroborated through further simulation and experimental work.

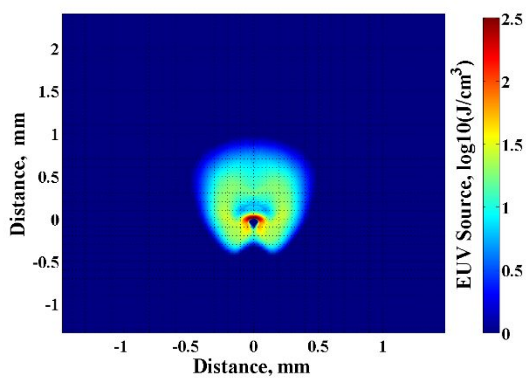
A large, 500 μm spot size of $CO_2$ laser was used in the above analysis. This results in a relatively large EUV source that could be difficult to collect within the etendue limit. Figures 10 shows the effect of the main-pulse spot size on the size of EUV source. Decreasing spot diameter from 500 μm (Fig. 10.a) to 300 μm (Fig 10.c) resulted in significant, ~30%, reduction in the CE of the source. Using laser beam with 400 μm diameter, however, allowed producing the source with acceptable size (Fig. 10.b) and without significant reduction in the efficiency, only from 4.8% to 4.5%.




a)




b)




c)

Figure 10. Integrated EUV sources produced by $CO_2$ laser with different spot sizes: a) 500 μm; b) 400 μm; c) 300 μm.

## 4. NEXT STEPS

Further efforts in plasma modeling, optical design, and experimentation will be needed to realistically ascertain the potential of power recycling, taking into consideration practical limitations of how to fit the recycling optics inside the plasma chamber. The HEIGHTS modeling will need to be refined to accurately replicate the performance of a commercial, baseline LPP system without power recycling. A fully specified optical design for the power-recycling system will be required to predict its performance, but before the design task can be completed some additional simulations will need to be done to guide the optical design and to enhance its performance.

First, the spectrum of the OoB radiation will need to be fully characterized. To an extent, this can be done through empirical measurement, but simulations can provide additional information on how efficiently different spectral wavelengths can be reabsorbed by the plasma taking into account any spectral changes resulting from feedback interactions with power recycling.

The current study also showed that recycling of the 10.6-$\mu$m laser radiation in dual-pulse system provides no significant benefit. This can be explained by the enhanced absorption of laser radiation in an expanded vapor/plasma plume. Other studies showed that significant increase in $CO_2$ laser absorption can be achieved by optimizing, e.g., the pre-pulse laser energy [20]. The optical design would be significantly impacted if there is no need to recycle long-wave infrared. Comparatively small corner-cube reflectors could be used because aperture diffraction would be much less significant at shorter wavelengths. It may also be possible to use total-internal-reflection (TIR) prism reflectors such as $MgF_2$ or $CaF_2$, and the axicon could possibly also be a TIR device. On the other hand, recycling of shorter wavelengths in the collector light path might not be practical unless the EUV mirror coating can be modified to improve its reflectivity at visible and lower wavelengths. If the collector's OoB reflectance cannot be significantly improved, then the optimum collector aperture size (collection angle) would be expected to be smaller with power recycling because the marginal loss in collection efficiency from a smaller aperture will be offset by more recycled power from outside the collector.

A second issue that needs to be addressed through simulation is the effect of the recycling time delay resulting from the finite light speed ($300\,\mathrm{mm/ns}$). This could dictate whether recycling optics require long, extended light paths or short light paths. Typically, the $CO_2$ laser pulse is irregular, with multiple, short bursts in each pulse (e.g., see Fig. 6 in [21]). The power-recycling reflectors could possibly be positioned to control the timing of the reflected radiation, effectively smoothing out the pulse irregularities.

Aside from modeling and optical design, the EUV monochromator grating will also require some engineering development work. Lawrence Berkeley Laboratory (LBL) has manufactured blazed EUV gratings with very short periods ($190\,\mathrm{nm}$, actually shorter than the multilayer depth) [22]. The same process, scaled to much larger periods, would establish feasibility of LPP monochromator gratings and would provide information on the achievable diffraction efficiency. (Efficiency can be improved by using second- or higher-order gratings, as LBL has demonstrated.) The challenge for EUV LPP systems will be manufacturing such gratings on large, curved substrates with adequate surface smoothness. Rigaku has demonstrated a surface-smoothing process that could be applicable to EUV gratings [13], and it might also be possible to circumvent the smoothing problem by using patterned multilayer gratings [6]. These grating types might require development of new manufacturing tools and processes, such as a focused-ion-beam lathe for mirror surface patterning.

The monochromator grating could, by itself, provide 100% OoB rejection with only a simple replacement of the collection mirror. But power recycling would require a more extensive system upgrade.

## 5. CONCLUSIONS

Power recycling provides a potential avenue toward higher EUV-LPP source efficiencies that will be needed for future lithography nodes. We have developed optical methodologies for recycling radiation both within and outside of the collector light path, including an EUV grating monochromator design that could achieve 100% rejection of OoB radiation. Our preliminary plasma simulations indicate that a 60% efficiency gain or higher might be possible with a dual-pulse system. Further simulation work will be required to more realistically and accurately ascertain the potential of power recycling and to provide guidance for engineering implementation and design optimization.

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