Characterization of plasmas driven by laser wavelengths in the 1.064 – 10.6 μm range as future extreme ultraviolet light sources

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We characterize the properties of extreme ultraviolet (EUV) light source plasmas driven by laser wavelengths in the \( \lambda_{\text{laser}} = 1.064 – 10.6 \mu m \) range. Detailed numerical simulations of laser-irradiated spherical tin microdroplet targets reveal a strong laser-wavelength dependence on laser light absorptivity and the conversion efficiency of generating EUV radiation. Radiative losses are found to dominate the power balance for all laser wavelengths, and a clear shift from kinetic to in-band radiative losses with increasing laser wavelength is identified. We find that the existence of maximum conversion efficiency, near \( \lambda_{\text{laser}} = 4 \mu m \), originates from the interplay between the optical depths of the laser light and the in-band EUV photons for this specific target geometry.

Extreme ultraviolet lithography (EUVL) is driving mass-production of today’s most advanced integrated circuits (ICs). Crucial to the success of this technology has been the development of a sufficiently powerful, stable and “clean” source of EUV radiation. Mass-production of today’s most advanced integrated circuits (ICs) and rapid developments in the interplay between the optical depths of the laser light and the in-band EUV photons for this specific target geometry.

We have performed numerical simulations of laser-produced tin plasmas using the two-dimensional radiation-hydrodynamic code RALEF-2D tailored for EUV source applications. In brief, the code solves the single-fluid, single-temperature hydrodynamic equations incorporating radiation transfer and thermal conduction processes. Spectral absorption coefficients and equation-of-state parameters are derived from the THERMOS code and the Frankfurt equation-of-state (FEOS) model, respectively. Laser light absorption and reflection is treated using a hybrid model combining a geometrical-optics ray-tracing...
approach in low-density plasma regions and a wave-optics approach in regions near and beyond the critical electron density. Laser absorption coefficients are derived from the complex dielectric permittivity of the plasma as per the Drude model.

The simulated cases consider laser irradiation of 30-μm-diameter liquid tin droplets, close to the industry standard, with spatially constant laser fluences of 60 μJ/cm² in width. The laser pulses are temporally trapezoidal-shaped with pulse lengths of 20 ns (rise and fall times of 0.2 ns). These experimental parameters are prototypical for recent simulation and experimental works alike (see, e.g., Refs. 9, 25, 30, 32, 33, 49–55). The laser wavelengths considered in this work are λ_{laser} = 1.064, 2, 3, 4, 5, 7, and 10.6 μm. This encompasses two distinct regimes of laser absorption, where absorption occurs primarily in the (i) underdense corona (for small λ_{laser}) or (ii) a narrow region near the critical surface (for long λ_{laser}).

The laser intensity is scaled according to I_{laser} = (1.4 × 10^{11})/λ_{laser} W/cm², an experimentally-motivated scaling which yields high conversion efficiencies for the laser wavelengths considered in this study. We note the close similarity between this scaling and the optimum laser intensity I_{laser} ∝ λ_{laser}^{-1.2} proposed by Nishihara et al.

In Fig. 1 we provide a still of the plasma formation induced by the four laser wavelengths λ_{laser} = 1.064, 2, 4, 10.6 μm at the time t = 18 ns after the laser pulse is switched on. The absorbed laser power per unit volume normalized by the input laser power, denoted ζ_{abs}, is shown in the upper halves of the panels. We find that with increasing λ_{laser}, the laser absorption zone moves further away from the droplet (blue region) due to the inverse square dependence of n_e,cr (white contours) on λ_{laser} and the electron density gradient associated with the near-spherical flow n_e ∝ r^{-2}. Moreover, the spatial extent over which the laser light is absorbed reduces with increasing λ_{laser}, a direct result of the aforementioned transitioning between the two distinct regimes of laser absorption. This is exemplified in the inset of panel (a), which shows the electron density and ζ_{abs} along the laser axis for λ_{laser} = 1.064 (square meshing) and 10.6 μm (diamond meshing). The steep electron density gradient precludes efficient absorption of long-wavelength laser light. In panel (d), we see that CO₂ laser absorption is restricted to a narrow region in front of the critical surface. Adopting Kramers cross section for inverse bremsstrahlung and assuming a (i) constant-temperature laser absorption zone and (ii) n_e ∝ r^{-2} profile, the optical depth of laser light τ_{laser} can be written...
where $Z$, $\ln(\Lambda)$, $T$, $R_{mc}$ and $a_{uv}$ are the charge state, Coulomb logarithm, temperature (in hundreds of eV), radius of the critical surface and a dimensionless parameter determining the position of laser absorption. Inferring appropriate values from our simulations, we estimate $\tau_{1.064 \mu m} \approx 10$ and $\tau_{1.066 \mu m} \approx 1$ as orders of magnitude for the present illumination geometry.

In the bottom halves of Fig. 1, we show the net in-band radiated power per unit volume normalized by the input laser power, denoted $\zeta_{in-band}$. This provides a local measure of the efficiency of converting laser light to in-band radiation. Of the four cases shown, the $4 \mu m$-driven plasma exhibits the highest $\zeta_{in-band}$ due to an optimum combination of intermediate laser absorptivity and intermediate optical depth of EUV photons (see Fig. 1 and the discussion below). We see that with increasing $\lambda_{laser}$, the region of net in-band emission (purple regions) moves from regions with $n_e < n_{e,cr}$ to regions with $n_e > n_{e,cr}$. Furthermore, the regions of net absorption of in-band radiation (orange regions) are located close to the droplet (regions with high densities and low temperatures), which will improve material ablation from the droplet surface.

The instantaneous partitioning of laser power during $\lambda_{laser} = 4 \mu m$ illumination is shown in Fig. 2. In Fig. 2, we show the input $P_{las}$ (black), absorbed $P_{abs}$ (blue), reflected $P_{ref}$ (orange) and “escaped” $P_{esc}$ (brown) laser power components. The escaped component represents laser radiation that initially misses the target, a quantity which decreases rapidly as the plasma expands and starts absorbing incident laser radiation. After 5 ns, a “steady-state” plasma flow regime is established whereafter $P_{abs}$ and $P_{ref}$ attain near-constant values. This behaviour is evident in the plasma-based components $P_{int}$ (internal power — derived from the specific Helmholtz free energy green), $P_{kin}$ (kinetic power, red), $P_{rad}$ (total
radiated power, purple) and $P_{\text{inb}}$ (in-band power, pink) shown in Fig.3(b). It is well-known that plasmas containing high-$Z$ ions exhibit large radiative losses, and our simulations indicate that approximately 70% of the absorbed laser power is channeled into radiation. Moreover, we find that nearly 16% of this radiation is concentrated in the in-band region, a surprisingly large fraction given the narrowness ($0.27\text{ nm}$) of this wavelength region.

Finally, we quantify power partitioning as a function of laser wavelength. This enables a comprehensive characterization of EUV plasma source conditions, where high laser absorptivities coupled with large in-band radiative losses and minimal kinetic losses are most desired. In Fig.3(a), we show the ratios $P_{\text{abs}}/P_{\text{las}}$ (blue) and $P_{\text{rad}}/P_{\text{las}}$ (red circles), and $P_{\text{kin}}/P_{\text{abs}}$ (pink triangles), and $P_{\text{inb}}/P_{\text{abs}}$ (green inverted triangles). The origin of these power laws is not exactly known, and they most likely originate from a complex interplay of radiation-transport, laser absorption and plasma expansion effects. The 1D planar isothermal expansion model of Murakami et al.\cite{murakami}, for example, predicts that $P_{\text{kin}}/P_{\text{rad}} \propto \lambda_{\text{laser}}^{-2} T^{-5/2}$, a much stronger dependence on $\lambda_{\text{laser}}$ than the $\lambda_{\text{laser}}^{0.3}$ power law found in the present simulations. In addition to 2D expansion effects, this discrepancy may be attributed to the assumption in Murakami et al.\cite{murakami} that laser absorption occurs entirely at the critical surface, which is not true for short-wavelength lasers.\cite{Bock, et al.}\cite{murakami} With increasing $\lambda_{\text{laser}}$ (and therefore decreasing plasma density), the optical depth of EUV photons reduces from $\tau_{\text{EUV}} \approx 6$ (Nd:YAG-driven plasma) to $\tau_{\text{EUV}} \approx 0.5$ (CO$_2$-driven plasma).\cite{key} This limits the degree of spectral broadening and redistribution of in-band energy into other channels, which explains the observed increase of $P_{\text{inb}}/P_{\text{abs}}$ with increasing $\lambda_{\text{laser}}$, and the behaviour of the spectral purity $\text{SP}_P = P_{\text{inb}}/P_{\text{rad}}$ (defined in the full $4\pi$) presented in Fig.3(c). As the relative fraction of radiative losses increases with increasing $\lambda_{\text{laser}}$, the balance dictates a corresponding decrease of kinetic losses.

The efficiency of producing in-band EUV radiation as a function of laser wavelength is shown in Fig.3(c). The conversion efficiency $C_{\text{E}}$ (black squares) exhibits a concave dependence on $\lambda_{\text{laser}}$ with a maximum at $\lambda_{\text{laser}} = 4\mu m$. This maximum arises from the rather unique combination of laser absorptivity and $\tau_{\text{EUV}}$ values. In essence, the plasma conditions are in a “sweet spot” intermediate to the extreme cases of high laser absorptivity/low spectral efficiency ($\lambda_{\text{laser}} = 1.064\mu m$) and low absorptivity/high spectral efficiency ($\lambda_{\text{laser}} = 10.6\mu m$).

This explains the simulation results of Langer et al., who identified an optimum for $\lambda_{\text{laser}} = 4.5\mu m$ irradiation of a one-dimensional tin vapour target.\cite{Langer} It is worthwhile noting that the maximum is located on a rather flat part of the curve between 3 and 5 $\mu m$, and that the CE$P$ increase from 1.064 $\mu m$ to 2 $\mu m$ is rather substantial, in line with experimental observations.\cite{Steur}

The strong dependence of conversion efficiency on laser absorptivity for $\lambda_{\text{laser}} > 4\mu m$ substantiates the opportunity to improve CE$P$ for long laser wavelengths. In Fig.3(c), we plot the quantity $C_{\text{E}}/(P_{\text{abs}}/P_{\text{las}})$ (grey squares), which represents the conversion efficiency if the absorption fraction would be unity for all laser wavelengths. This quantity increases monotonically with increasing $\lambda_{\text{laser}}$, plateauing between $\lambda_{\text{laser}} = 7$ and 10.6 $\mu m$. This behaviour can be understood qualitatively from the power balance model of Murakami et al.\cite{murakami}, where, denoting $\eta_C = C_{\text{E}}/(P_{\text{abs}}/P_{\text{las}})$, the model predicts that

$$\eta_C \approx 2g_{2D} \left(1 + \frac{5P_{\text{kin}}}{2P_{\text{rad}}}\right)^{-1} \frac{S_{\text{EUV}}}{\sigma T^2}$$

where $g_{2D}$ is a factor accounting for 2D effects, $S_{\text{EUV}}$ is the in-band emissivity and $\sigma$ is the Stefan-Boltzmann constant. Kinetic losses decrease with increasing laser wavelength. In fact, as $\lambda_{\text{laser}} \rightarrow \infty$, $P_{\text{kin}}/P_{\text{rad}} \propto \lambda_{\text{laser}}^{2} T^{-5/2} \rightarrow \eta_{C}$ as $2g_{2D}S_{\text{EUV}}/\sigma T^4$, behaviour which is consistent with the plateau observed in Fig.3(c). In order to increase laser absorptivity for long $\lambda_{\text{laser}}$, one could pre-irradiate the target to convert it into a rarefied, spatially extended medium. This would decrease the plasma density gradient and subsequently increase the laser optical depth and, thus, its absorption in the plasma. Such target pre-shaping has been successfully applied in industrial applications, enabling high conversion efficiencies from CO$_2$ laser-irradiated tin target.\cite{Steur} That said, target shaping remains unexplored in the intermediate wavelength region considered in this work, and this may lead to substantial increases in CE$P$.

In summary, we have investigated the power partitioning in a laser-produced tin plasma for laser wavelengths in the $1.064 \leq \lambda_{\text{laser}} \leq 10.6\mu m$ range. We have identified a strong laser-wavelength dependence of laser absorptivity and the location of EUV generation. With increasing laser wavelength, the power balance monotonically shifts from kinetic losses to in-band radiative losses. The decrease in laser absorption for long laser wavelengths, combined with an concurrent decrease in EUV optical depth, yields a non-monotonic behaviour of the conversion efficiency, leading to an optimum at $\lambda_{\text{laser}} = 4\mu m$. EUV sources based on long laser wavelengths would benefit from additional target preparation to ensure a higher absorption fraction.
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