Time-resolved two-dimensional profiles of electron density and temperature of laser-produced tin plasmas for extreme-ultraviolet lithography light sources

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Time-resolved two-dimensional (2D) profiles of electron density ($n_e$) and electron temperature ($T_e$) of extreme ultraviolet (EUV) lithography light source plasmas were obtained from the ion components of collective Thomson scattering (CTS) spectra. The highest EUV conversion efficiency (CE) of 4% from double pulse lasers irradiating a Sn droplet was obtained by changing their delay time. The 2D-CTS results clarified that for the highest CE condition, a hollow-like density profile was formed, i.e., the high density region existed not on the central axis but in a part with a certain radius. The 2D profile of the in-band EUV emissivity ($\eta_{EUV}$) was theoretically calculated using the CTS results and atomic model (Hullac code), which reproduced a directly measured EUV image reasonably well. The CTS results strongly indicated the necessity of optimizing 2D plasma profiles to improve the CE in the future.

Extreme-ultraviolet lithography is a promising technology for high-volume manufacturing of next-generation semiconductor devices. A carbon dioxide (CO$_2$) drive laser and a tin droplet target are used as an efficient extreme-ultraviolet (EUV) light source. One of the primary challenges involves the improvement of the conversion efficiency (CE) from laser energy to in-band EUV energy at a wavelength of $\lambda = 13.5$ nm (2% full-bandwidth). Debris reduction is also a crucial problem for commercial usage. Therefore, mass-limited targets, such as small Sn droplets with a diameter on the order of 20 $\mu$m, have been introduced. However, it is desirable to have a large EUV plasma volume within the etendue limits to achieve a large EUV emission. A double-pulse irradiation scheme is proposed, where a pre-pulse laser expands a small tin droplet, and the main laser irradiates when it reaches a size of approximately 300 $\mu$m in diameter. A CE of approximately 4% was confirmed using this approach.

A strong correlation has recently been shown between the laser absorption and the CE by changing the delay time between the pre- and main-pulse lasers. However, the reported CE was approximately 2% at the highest. The EUV emissivity strongly depends on plasma parameters, such as electron density ($n_e$), electron temperature ($T_e$), and average ion charge state ($Z$). Hence, we developed a collective Thomson scattering (CTS) system to measure these parameters. In our previous study, it was confirmed that adequate $n_e$ and $T_e$ were achieved in the EUV light source plasmas, but this did not provide optimum plasma conditions for high CE.

This paper determined for the first time that it is important to generate a plasma with an optimal two-dimensional (2D) structure to achieve a large EUV conversion efficiency by adding theoretical analysis to...
the 2D-CTS data, unlike the contents of our previous paper\textsuperscript{17}. That is, it is very important to increase the plasma volume, satisfying the optimum conditions for EUV light emission within the range of the permitted etendue condition.

We specifically showed in this manuscript that the plasma expands to a large radius region, and a hollow-like structure of the optimum plasma efficiently emitting EUV is formed under ideal conditions.

**Results**

Figure 1(a) schematically shows the experimental set-up\textsuperscript{17}. A droplet generator supplied the Sn droplet target (diameter: 26 μm) inside a vacuum chamber (<10\textsuperscript{-4} Pa). The pre-pulse and main lasers propagated in the x direction and irradiated the droplet. The x, y, and z axes are defined in Fig. 1(a), where the droplets fell in the z direction. The origin of the coordinate was set to the initial droplet position before the pre-pulse irradiation. The pre-pulse laser was a Nd:YVO\textsubscript{4} laser with a 14 ps pulse width [full width at half maximum (FWHM)], a 2 mJ laser energy at 1064 nm, and a spot diameter of 66 μm \( (1/e^2) \) intensity at the droplet position. The diameter of the 1\( /e^2 \) intensity was used for the laser spot size. The main laser was a CO\textsubscript{2} laser with a 15 ns pulse width (FWHM), 100 mJ at 10.6 μm, and a spot diameter of 400 μm. Figure 1(b) and (c) show shadowgraphs of the initial tin droplet and that of the expanded tin droplet at 2.0 μs after the pre-pulse irradiation, respectively. Time-integrated, in-band EUV images were observed in the negative y axis direction [Fig. 1(d)]. The in-band EUV radiation was measured with an EUV energy sensor located at an angle of 150° in the x axis [Fig. 1(a)].

The probe laser for the CTS was the second harmonic of a Nd:YAG laser with a spectral linewidth below <0.1 pm (FWHM) (pulse width: 6 ns FWHM, 3–10 mJ, wavelength λ\textsubscript{p}=532 nm, spot diameter of 30 μm in the scattering volume). All three lasers had identical beam paths. The CTS signals were collected by lenses at an angle of 120° from the incident laser direction, focusing on the entrance slit of the spectrometer (20 μm width and 5 mm height) and detected by an intensified charge-coupled device (ICCD) camera (Princeton Instruments, PI-MAX4, 45% quantum efficiency at λ\textsubscript{e}). The x axis dimension of the scattering volume was imaged in the slit height direction. Therefore, one-dimensional, spatially resolved measurements were achieved at the same time\textsuperscript{16,15}. The CTS measurements were repeated over 30 times at identical experimental conditions. The sufficient reproducibility of the spectra was also confirmed. Regarding the plasma heating by the probe laser, the relative temperature increase \( (∆T/T) \) was discussed in a previous paper\textsuperscript{18} based on a model considering the absorption by the inverse bremsstrahlung and of the heat transport to the volume surrounding the laser beam during the laser pulse\textsuperscript{19,20}. As a result, ∆\( T/T \) was estimated to be less than 3% for the cases reported here.

The CE for a solid angle of 2 π sr was calculated assuming an isotropic distribution of the EUV radiation. Figure 1(e) shows the typical waveforms of the main and probe lasers. As shown in this figure, the time zero \( (t=0 \text{ ns}) \) for the CTS measurements was of the first peak of the main laser\textsuperscript{17}.

The absolute CE measurements showed that the plasma produced at the delay time of \( t_0=2.0 \mu s \) (hereafter referred to as 2.0 μs plasma) had the maximum CE herein (i.e., 4.0%). The CE values for the 1.3 μs and 2.5 μs plasmas decreased to 3.1% and 2.8%, respectively. These three different plasmas were diagnosed by CTS to investigate the relation between the CE and the plasma parameters.

The CTS measurements were performed at 0, 50, 100, 200, and 300 μm in the y axis direction [Fig. 1(a)] and at times of \( t=5, 10, \text{ and } 15 \text{ ns} \) [Fig. 1(e)]. Sufficient symmetry of the plasma along the y-axis was confirmed in the complementary CTS measurements in the negative y-axis \( (y=−100, −200, \text{ and } −300 \mu m) \) at \( t=10 \text{ ns} \). The spatial resolutions of the measurements were 13, 50, and 20 μm for the x, y, and z axes, respectively [Fig. 1(a)]. These resolutions were determined by the pixel size of the ICCD camera (13 μm, laser spot size (50 μm), and entrance slit width (20 μm)). The time resolution was determined by the ICCD camera gate width of 5 ns. Figure 1(f) presents a typical, single-probe laser pulse CTS image for the 2.0 μs plasma at \( t=10 \text{ ns} \) and at \( y=0 \). The horizontal axis in the figure is the x axis (i.e., laser propagation axis), while the vertical axis is the wavelength difference \( ∆λ \) from λ\textsubscript{e}. The dark area at \( ∆λ=0 \) (within the width of ±14 pm from λ\textsubscript{e}) is the discussed wavelength suppression to reduce the stray light\textsuperscript{16}.

Figure 1(g) illustrates the spectrum at 15 < x < 45 μm of Fig. 1(f) and its fitting curve. We note that the absolute calibration of the CTS system was performed by Rayleigh scattering measurements from nitrogen gas. The vertical (y-axis) scan of CTS measurements was performed by moving the focusing position of the probe laser. The absolute calibration of the CTS system was performed at each y position. By using the methods described in the following Method section, \( n_e, T_e \) (\( = T_i \)), and Z were determined as 3.6 × 10\textsuperscript{24} m\textsuperscript{-3}, 38 eV, and 12, respectively. The shift of the entire spectrum from λ\textsubscript{e} was caused by Doppler shift, which reflected a plasma drift velocity in the \( k \) direction of approximately 1.2 × 10\textsuperscript{3} m/s.

Figure 2(a) shows the electron density profiles at different y positions from the 2.0 μs plasma at a time of \( t=10 \text{ ns} \). Figure 2(b)–(d) demonstrate the contour plots of \( n_e, T_e \), and Z in the x–y planes, respectively. Figure 2(e) presents the local in-band EUV emissivity \( η_{\text{EUV}} \) (W/m\textsuperscript{3}/eV/sr) calculated as a function of x and y from the measured values of \( n_e, T_e \), and Z and the atomic model based on the Hallac code\textsuperscript{17}. Intense \( η_{\text{EUV}} \), occurred, where a high electron density \( (≥4 × 10^{24} \text{ m}^{-3}) \) and a high temperature \( (≥25 \text{ eV}) \) were simultaneously observed. Note that the plasma cut-off density of the CO\textsubscript{2} laser was 10\textsuperscript{23} m\textsuperscript{-3}.

Figure 3(a) and (b) show the \( η_{\text{EUV}} \) profiles of the 2.0 μs plasma measured at time \( t=5 \text{ and } 15 \text{ ns} \), respectively. By comparing Fig. 3(a) and (b) with Fig. 2(e), we found that the EUV emission was clearly the strongest at approximately 10 ns. Figure 3(c) shows the sum of the \( η_{\text{EUV}} \) profiles displayed in Figs 2(e) and 3(a) and (b). The large emissivity of \( ≥2.5 × 10^{15} \text{ W/m}^3/\text{eV/sr} \) occurred at approximately y=50–100 μm. The measured EUV image shown in Fig. 1(d) has its maximum at y=0 μm. We calculated the in-band EUV intensity (W/m\textsuperscript{3}/eV/sr) represented in Fig. 3(d) from the emissivity profiles [shown in Fig. 3(c)] by solving the radiation transport along the line of sight with taking the plasma self-absorption into account under the assumption of the axial symmetry of the plasma profiles. The plasma self-absorption was calculated from in-band opacity represented in Fig. 15(e) of ref.\textsuperscript{15}. The ray trace method [e.g., ref.\textsuperscript{21} and similarly Eq. (8) in ref.\textsuperscript{13}] was used to calculate the radiation transport. The profiles shown in Fig. 1(d) (measured) and Fig. 3(d) (calculated using the CTS results) agreed considerably
well. For instance, both showed the maximum EUV radiation on the laser axis ($y = 0$). The calculated EUV image [Fig. 3(d)] did not consider the emissivity at times $<3$ ns. Hence, the EUV image was slightly thinner (narrower) at the laser irradiation side than the measured image in Fig. 1(d).

Figure 4 represents the shadowgraphs and the spatial profiles of $n_e$, $T_e$, and $\eta_{\text{EUV}}$ of the three plasma conditions (i.e., $t_d = 1.3$, 2.0, and 2.5 $\mu$s) measured at $t = 10$ ns. Figure 4(a)–(c) show the shadowgraphs, while Fig. 4(d)–(f) and (g)–(i) demonstrate the $n_e$ and $T_e$ profiles, respectively. Figure 4(j)–(l) show the $\eta_{\text{EUV}}$ profiles calculated from...
the corresponding plasma parameters of the three different plasmas. The measured data were interpolated in Fig. 4(d)–(l). Figure 4(e),(h), and (k) use the same data set as in Fig. 2(b),(c), and (e), respectively.

Discussion

We now discuss the relation between the CE and the spatial profiles of $n_e$, $T_e$, and $\eta_{EUV}$ for the three plasmas shown in Fig. 4(d)–(l). For the case of the 1.3 $\mu$s plasma, the high $T_e$ (>25 eV) region, in which the tin ion can emit the intense EUV, localized at $x < 0$. In contrast, the high electron density mainly existed at $x > 0$. The high $T_e$ and the high $n_e$ were simultaneously achieved in only the small area at approximately $x = 0$ [Fig. 4(d) and (g)].

As is apparent from Fig. 4(d) and (e), a large difference in the electron density profile existed between the 1.3 $\mu$s and 2.0 $\mu$s plasmas. It should be noted that the $y$ direction corresponded to the radial one. The plasma also expanded in the radial direction after the pre-pulse laser irradiation. Hence, the Sn density near the $x$ axis decreased, and a hollow density profile was formed in the case of the 2.0 $\mu$s plasma. We believe that this hollow density profile of the 2.0 $\mu$s plasma was a major factor for the high conversion efficiency of 4%.

Figure 4(j) and (k) show that the maximum EUV emissivity values were almost identical. The maximum values were 1.2 and $1.4 \times 10^{15}$ W/m$^3$/eV/sr, respectively. However, the high radiation region for the 1.3 $\mu$s plasma existed in only the vicinity of the $x$ axis (i.e., the axis of the laser irradiation), whereas the large emissivity region for the 2.0 $\mu$s plasma existed for the radius between 30 $\mu$m and 150 $\mu$m (i.e., $30 \mu$m $\leq y = r \leq 150 \mu$m). The total EUV radiation was given by the volume integration of the emissivity $\eta_{EUV}$. Therefore, the intense emissivity $\eta_{EUV}$
at the larger radius mostly contributed to the total EUV radiation. The emitted EUV energy for the 2.0 μs plasma was much larger than that for the 1.3 μs plasma because of the higher emissivity in the region of the larger radius.

On the contrary, the region with $T_e \geq 25$ eV for the 2.5 μs plasma spread in a wide area both in the x and radial directions. However, the maximum emissivity was only $0.9 \times 10^{15}$ W/m$^3$/eV/sr. The plasma expanded, and the electron density decreased below $4 \times 10^{24}$ m$^{-3}$ in the high-temperature region because of the long delay time.

We estimated the in-band EUV energies from the emissivity shown in Fig. 4(j)–(l) for the three plasma cases under the following assumptions: axial symmetry, isotropic distributions of the EUV radiation, without self-absorption, and an EUV duration of 20 ns. The obtained values were 2.1 mJ, 4.0 mJ, and 1.8 mJ for the 1.3 μs, 2.0 μs, and 2.5 μs plasmas, respectively. Although these values were calculated under the above assumptions, the calculated EUV energies approximately agree with the calorimetric measurements.

The details of the difference in the electron density and the temperature between the 1.3 μs and 2.0 μs plasmas can now be compared. A density region higher than the critical density existed for the 1.3 μs plasma at a radius of $r \leq 150$ μm and an x position of $0 \mu m \leq x \leq 150 \mu m$. This region has a sharp density gradient near the critical density. As a result, a high-temperature region suitable for the EUV light emission of $T_e \geq 25$ eV and a high-electron density region ($4 \times 10^{24} m^{-3} \leq n_e \leq 8 \times 10^{24} m^{-3}$) existed separately. The EUV radiation region was indeed small not only in the radial direction but also in the x direction. On the contrary, both a wide region of high electron temperature ($T_e \geq 25$ eV) and high electron density ($4 \times 10^{24} m^{-3} \leq n_e \leq 8 \times 10^{24} m^{-3}$) existed for the 2.0 μs plasma not only in the x-direction but also in the radial direction. Most importantly, the regions of high electron temperature and high density largely overlapped in both directions. In other words, the large volume of the good parameter range was the reason for the high conversion efficiency. Note that $\eta_{\text{EUV}}$ has a strong nonlinearity with $T_e$, as shown in Fig. 15(d) in ref. 12.

Here we briefly describe the expansion of the droplets. Figures 1(c) and 4(a),(c) show that the spatial distributions and the sizes of the tin fragments were inhomogeneous. However, we have confirmed good reproducibility of their macroscopic behaviors, e.g., the time evolution of the diameters and the whole images of the expanding target.

Accordingly, collective Thomson scattering measurements were applied to laser-produced EUV light source plasmas. For the first time, the detailed measurements of the ion component spectra resulted in the time-resolved two-dimensional spatial profiles of $n_e$, $T_e$, and $Z$. The following results were experimentally obtained:

1. the two-dimensional plasma profiles of the electron density and temperature significantly changed with the delay time between the pre-pulse and main lasers; and
2. an electron density of $(4–8) \times 10^{24} m^{-3}$ and an electron temperature of $\geq 25$ eV were simultaneously observed for the highest CE in the largest plasma volume (i.e., a good plasma structure was obtained).

The formation of this good electron density $(4–8) \times 10^{24} m^{-3}$ and temperature $(\geq 25$ eV) profile may outline further improvements toward a higher CE in the future. We believe that these straightforward results obtained from the measured plasma parameters are very useful to further understand and optimize laser-produced plasma light sources for EUV emission.
Method

Collective Thomson scattering. Here, the principle of the CTS is briefly described\(^{22,23}\). The predicted Thomson scattering spectra from the EUV light source plasmas are in the collective regime when a visible probe laser is used (i.e., the scattering parameter \( \alpha \) is larger than 1 \( \left[ \alpha = \left( \frac{k}{\lambda_D} \right)^2 - 1 \right] \), where \( \lambda_D \) is the Debye length, and \( k \) is the absolute value of the differential scattering vector defined as \( k = k_s - k_i \); \( k_i \) and \( k_s \) are the wavevectors of the incident probe laser and the scattered light, respectively). The Thomson scattering spectrum in this regime comprises both an electron and an ion component\(^{24,25}\). Considering the strong background radiation from the plasma, we focused on only the ion component, for which we expected large signal-to-noise ratios against the background radiation even for a small probe-laser energy to avoid plasma heating\(^{26,27}\). The ion component spectrum reflects the ion acoustic wave frequency \( \omega_{ac} = k \left[ \alpha^2(1 + \alpha) \right] \left( \frac{Z\kappa T_e + 3\kappa T_i}{m_i} \right)^{1/2} \), where \( \kappa \) is the Boltzmann constant, \( m_i \) is the ion mass, and \( T_i \) is the ion temperature. The spectrum exhibits two peaks (i.e., ion features with a dip between them). The wavelength separation \( 2\Delta \lambda_{peak} \) of the two peaks is related to the probe laser wavelength \( \lambda_0 \) and \( \omega_{ac} \) by \( \Delta \lambda_{peak} = \frac{\lambda_0^2 \omega_{ac}}{2\pi c} \), where \( c \) is the speed of light. \( ZT_e \) and \( T_i \) are obtained from the width \( \Delta \lambda_{peak} \) and the spectral shape, which is characterized by ion acoustic wave damping\(^{24,25}\). In addition, \( n_e \) is determined by an absolute calibration of the CTS system because the scattered light intensity is proportional to the electron density. All of the plasma parameters (i.e., \( T_e, n_e, \) and \( Z \)) are then determined assuming \( T_i = T_e \).

The CTS was applied to various laser-produced plasmas (LPPs)\(^{28-31}\). However, a special challenge for the EUV light source plasmas is the very small wavelength separation of the ion features of \( \sim 100 \) pm at \( \lambda_0 = 532 \) nm, which also means that the ion component is very close to the probe laser wavelength \( \lambda_0 \) (i.e., 50 pm). Therefore, very high spectral resolution and stray light reduction are essential. Triple grating spectrometers are widely used for collective and noncollective Thomson scattering\(^{32,33}\). However, a special challenge for the EUV light source plasmas is the very small wavelength separation of the ion features of \( \sim 100 \) pm at \( \lambda_0 = 532 \) nm, which also means that the ion component is very close to the probe laser wavelength \( \lambda_0 \) (i.e., 50 pm). Therefore, very high spectral resolution and stray light reduction are essential. Triple grating spectrometers are widely used for collective and noncollective Thomson scattering\(^{32,33}\). However, they block a wavelength range of approximately \( 1 \) nm at \( \lambda_0 \) to reduce stray light (i.e., the ion component in our application is also blocked). Therefore, we built a custom spectrometer\(^{14,37}\). This spectrometer has six gratings. Four gratings are used for stray light reduction, while the other two gratings are utilized for wavelength dispersion. Thus, a spectral resolution of \( 12 \) pm and a sufficient stray-light rejection with a very narrow wavelength block range (within \( \pm 14 \) pm from \( \lambda_0 = 532 \) nm) were achieved, and the ion components from the Sn plasmas for the LPP-EUV light sources were clearly observed\(^{14}\).
References
1. Tallents, G., Wagenaaars, E. & Pert, G. Optical lithography: Lithography at EUV wavelengths. Nature Photonics 4, 809–811 (2010).
2. Stamm, U. et al. High-power EUV lithography sources based on gas discharges and laser-produced plasmas. Proc. SPIE 5037, Emerg. Lithogr. Technol. VI 5037, 5037–119 (2003).
3. Mizoguchi, H. et al. LPP-EUV light source development for high volume manufacturing lithography, Proc. SPIE 867986790A (2013).
4. Tanaka, H. et al. Comparative study on emission characteristics of extreme ultraviolet radiation from CO2 and Nd:YAG laser-produced tin plasmas. Appl. Phys. Lett. 87, 5–8 (2005).
5. Ueno, Y. et al. Enhancement of extreme ultraviolet emission from a CO2 laser-produced Sn plasma using a cavity target. Appl. Phys. Lett. 91, 231501 (2007).
6. O’Sullivan, G. & Carroll, P. K. 4d–4f emission resonances in laser-produced plasmas. J. Opt. Soc. Am. 71, 227–30 (1981).
7. Fujikawa, S. et al. Pure-tin microdroplets irradiated with double laser pulses for efficient and minimum-mass extreme-ultraviolet light source production, Appl. Phys. Lett. 92 (2008).
8. Shimomura, M. et al. Neutral debris mitigation in laser produced extreme ultraviolet light source by the use of minimum-mass tin target. Appl. Phys. Express 1, 056001–3 (2008).
9. Bakshi, V. EUV Sources for Lithography, edited by V. Bakshi (SPIE Press Monograph, 2006).
10. Matsukuma, H. et al. Correlation between laser absorption and radiation conversion efficiency in laser produced tin plasma. Appl. Phys. Lett. 107, 3–7 (2015).
11. Sasaki, A. et al. Atomic modeling of the plasma EUV sources. High Energy Density Phys. 5, 147–51 (2009).
12. Sasaki, A. et al. Modeling of radiative properties of Sn plasmas for extreme-ultraviolet source. J. Appl. Phys. 107, 113303 (2010).
13. Nishihara, K. et al. Plasma physics and radiation hydrodynamics in developing an extreme ultraviolet light source for lithography. Phys. Plasmas 15, 36708 (2008).
14. Tomita, K. et al. Development of a collective Thomson scattering system for laser-produced tin plasmas for extreme-ultraviolet light sources. Appl. Phys. Express 8, 126101 (2015).
15. Tomita, K. et al. A collective laser-thomson scattering system for diagnostics of laser-produced plasmas for extreme ultraviolet light sources. Appl. Phys. Express 6 (2013).
16. Tomita, K. et al. Collective Thomson Scattering Diagnostics of EUV Plasmas. J. Plasma Fusion Res. Ser. 8, 488–91 (2009).
17. Sato, Y. et al. Spatial profiles of electron density, electron temperature, average ionic charge, and EUV emission of laser-produced Sn plasmas for EUV lithography. Jpn. J. Appl. Phys. 56, 36201 (2017).
18. Tomita, K., Hassaballa, S. & Uchino, K. Thomson Scattering Diagnostics of EUV Plasmas. J. Plasma Fusion Res Ser. 10, 056001–3 (2008).
19. Kubota, Y. et al. Neutral debris mitigation in laser produced extreme ultraviolet light source by the use of minimum-mass tin target. Appl. Phys. Express 1, 231701 (2007).
20. Sheffield, J. et al. Plasma scattering of electromagnetic radiation, 2nd Edition (Academic Press, 2010).
21. Evans, D. E. & Katzenstein, J. Laser light scattering in laboratory plasmas. Reports Prog. Phys. 32, 207–71 (1969).
22. Monta, T. et al. Thomson scattering measurement of a shock in laser-produced counter-streaming plasmas. Phys. Plasmas 20, 022115 (2013).
23. Tomita, K. et al. Thomson scattering diagnostics of SF6 gas-blasted arcs confined by a nozzle under free-recovery conditions. J. Phys. D: Appl. Phys. 48, 265201 (2015).
24. Kieff, E. R. et al. Collective Thomson scattering experiments on a tin vapor discharge in the prepinch phase. Phys. Rev. E 70, 56413 (2004).
25. Kieff, E. R., Mullen, J. J. A. M. & Banine, V. Subnanosecond Thomson scattering on a vacuum arc discharge in tin vapor. Phys. Rev. E 72, 26415 (2005).
26. Park, H. S. et al. Studying astrophysical collisionless shocks with counterstreaming plasmas from high power lasers. High Energy Density Phys. 8, 38–45 (2012).
27. Froula, D., Divol, L. & Glenerz, S. Measurements of Nonlinear Growth of Ion-Acoustic Waves in Two-Ion-Species Plasmas with Thomson Scattering, Phys. Rev. Lett. 88, 105003 (2002).
28. Ross, J. S. et al. Thomson scattering diagnostic for the measurement of ion species fraction, Rev. Sci. Instrum. 83, 10E323 (2012).
29. Fontaine, B. et al. Characterization of laser-produced plasmas by ultraviolet Thomson scattering, Phys. Plasmas 1, 2329 (1994).
30. Hassaballa, S. et al. Two-dimensional structure of PDP micro-discharge plasmas obtained using laser Thomson scattering, IEEE Trans. Plasma Sci. 32, 127–34 (2004).
31. Kono, A. & Nakatani, K. Efficient multichannel Thomson scattering measurement system for diagnostics of low-temperature plasmas. Rev. Sci. Instrum. 71, 2716 (2000).

Author Contributions
K.T. and K.U. designed the laser diagnostic system. K.T. and Y.S. built and performed the laser diagnostic experiments. K.K., H.T., T.Y., Y.W., and M.K. performed the operation of EUV light sources. K.T., K.U., G.S., T.K., H.M., A.S., and K.N. discussed the results. K.T., S.T., and T.E. prepared figures. K.T., G.S., A.S., and K.N. wrote the main manuscript text. All authors reviewed the manuscript.

Additional Information
Competing Interests: The authors declare that they have no competing interests.

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