Xe Laser-Plasma Source – from 13.5 to 11 nm:

Researches to Optimize the Xe LPP 11-nm Source

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Motivation

This work has been initiated by an idea of a further development of the EUV lithography proposed in the Institute for Physics of Microstructures (IPM), Nizhniy Novgorod, Russia: using the debrisless Xe laser plasma source with the working wavelength changed from $\lambda = 13.5$ to 11.2 nm. One of basements of the proposal was an expectation that the source emission would be 4-5 times more intensive at $\lambda \approx 11$nm than that at $\lambda = 13.5$ nm, whereby the 11-nm source could become competitive in comparison with the contemporary tin 13.5-nm source.

(N. I. Chkhalo and N. N. Salashchenko. AIP Advances 3 (2013), 082130. Also see in: 2013 EUV Source Workshop, Dublin, Ireland, S19.)

Results presented

1. Spectral measurements under a wide variety of experimental conditions (Braggs’ mirrors & spectrograph).

2. Suppression of the peripheral absorption of the EUV emission.

3. Absorption of the laser beam energy in the laser produced plasma.
Spectral measurements with Braggs’ mirrors

1 – IR lens
2 – IR laser beam
3 – jet generator with the Laval nozzle
4 – Xe ultrasonic jet
5 – line of observation
6 – interchangeable mirrors in a holder
7 – two angular scaleplates
8 – Si/Mo multilayer spectral filters in a holder
9 – Si photodiode with a preamplifier in a housing
Features & details common for all our experiments

Laser: Nd:YAG, $\lambda = 1064$ nm, $E_{\text{at plasma}} \approx 0.7\text{–}1.0$ J, $\tau_{\text{las}} \approx 10$ ns (FWHM)

Gas target:
Super sonic Xe jet flowing out from a Laval nozzle (alumina) into the vacuum.
Gas conditions were calculated with the aid of a fluid dynamics numerical simulation: $n_{\text{axis}} = (0.1\div 7) \times 10^{18}$ cm$^{-3}$, jet width (FWHM) = $0.7\div 1.4$ mm.

Si/Mo spectral purity filter. Typically 2 or 3 such filters were used.

Si surface-barrier photodiode.
Mo/Be and Si/Mo multilayer mirrors

Angular Mo/Be mirror characteristic at $\lambda = 11.4$ nm as measured in the IPM

Spectral characteristics of the Mo/Be mirror (1) and the Si/Mo one (2).

Mo/Be: $\lambda = 11.1 \div 11.8$ nm, Refl = 66-67 %, $\Delta \lambda = 3$ Å (FWHM)
Si/Mo: $\lambda = 12.6 \div 14.1$ nm, Refl = 62-66 %, $\Delta \lambda = 5$ Å (FWHM)
Results of measurements and reconstruction of the spectrum

Photodiode output signals:
1 – Mo/Be, 2 – Si/Mo.

Target density \((6-7) \times 10^{18} \text{ cm}^{-3}\);
\(\Delta X=1\text{mm from the nozzle outlet;}
\text{the beam focus is at the jet axis.}\)

A spectrum derived from the data above by means of approximate solving integral equations for two mirrors:

\[
U(\alpha) = A \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} I_\lambda(\lambda) R(\lambda, \alpha) T(\lambda) S(\lambda) d\lambda
\]
Spectrographic measurements at different experimental conditions

Densities from the bottom to the top ($10^{18}$ cm$^{-3}$): 0.4; 1.3; 2.2; 2.6; 3.1; 3.6; 4.1.

$E_{\text{las}} = 960$ mJ.
Outlet-to-focus distance – $\Delta X = 1$ mm.
The focus was shifted from the jet axis to the observer by half outlet radius.

$E_{\text{las}}$ from the bottom to the top:
370, 700, and 960 mJ.
Density – $(6-7) \times 10^{18}$ cm$^{-3}$.
1) Height of the scattered light pedestal is determined for $\lambda = 11-14$ nm.
2) The spectrographic data are absolutely calibrated.
Spectral measurements – résumé

1) A spectra database has been obtained for different experimental conditions.

2) Spectral maxima reveal a trend to be shifted to shorter wavelengths side as both the density and the laser energy input increase (obviously, this is due to a plasma temperature growth). This implies a strong variability of the emission intensity just within the range of interest – $\lambda = 11.2 \div 11.4$ nm

3) A ratio of EUV intensities at the wavelengths of interest, $I_{11.2\text{nm}}/I_{13.5\text{nm}}$, amounts up to 10-11 at some definite conditions.

Authors thank Prof. John Costello (DCU) who advised us, some time, to turn our attention to the EUV spectroscopy of the Xe laser plasma.
Suppression of the peripheral absorption

Displacement of the focus relative to the jet axis towards the observer (along Z) yields a well-known result.
Movement of the jet along the laser beam axis (Y)

\[ \lambda = 13.5 \text{ nm} \]

\[ \lambda = 11.4 \text{ nm} \]
Explanatory hypothesis

Explanation of the wide beam irradiation effect can be as follows:

the peripheral gas, when being irradiated and heated with the widened laser beam, is converted into a plasma with mean ion charge of $Z_{\text{eff}} \geq 7$ and becomes transparent for EUV photons of interest because $h\nu < E_i$ ($h\nu \approx 100\text{eV}$ whereas $E_{i,\text{Xe}^7} = 106\text{ eV}$, $E_{i,\text{Xe}^8} = 180\text{ eV}$…).

Usually in our experiments with sharply focused beam, more than 90% EUV energy emitted by the hot plasma core is absorbed in the cold peripheral gas.
Two spectra at different laser irradiation geometries

Experimental conditions:
n_{\text{axis}} = 7 \times 10^{18} \text{ cm}^{-3}, E_{\text{las}} = 0.9 \text{ J}, \Delta X = 1\text{ mm}

\(\lambda\)-positions of maxima in these two spectra suggest that the temperature for the "wide beam case" is lower. But the gain due to the transparent periphery exceeds a probable decrease of the EUV emission due to the lower temperature.
Absorption of the laser radiation by the laser plasma

At jet densities $n_{i,\text{axis}} = (4-7) \times 10^{18} \text{ cm}^{-3}$ and effective diameter $\Theta_{\text{target}} \approx 700 \mu\text{m}$

the absorption was $\frac{I_{\text{abs}}}{I_0} = (41-43)\%$

Two features attract an attention:

1) The absorption is 2 times less than that expected from estimations
   
   $\frac{I_{\text{abs}}}{I_0} = 1 - \exp\{-\mu \ell_{\text{abs}}\}$, $\mu \sim n_i^2 <Z>^3/T^{3/2}$ at
   
   $<Z> = 10$, $T = 30 \text{ eV}$, $\ell_{\text{abs}} = 400-500 \mu\text{m}$ (equal to the caustic surface length)

2) The absorption stands constant in spite of density variations by a factor of 1.75.
The explanation – a nonlinearity of the absorption:

\[ \frac{dI_{\text{las}}}{d\ell} = -\mu I_{\text{las}}, \text{ where } \mu = \mu(I_{\text{las}}) \]

The plasma "head" faced to the laser is the hottest, the most ionized and, consequently, the most absorbing part of the spark. It absorbs about 30% laser energy. Long but colder and less ionized "tail" absorbs residual \( \approx 15\% \).

An effective absorption length turns out to be several times shorter than the caustic surface length within the the jet target:

\[ l_{\text{abs, eff}} < l_{\text{caustic}}, \quad l_{\text{abs, eff}} \approx 100\text{-}150 \, \mu\text{m} \]

The laser plasma looks like a self-consistent system:

\[ \mu(I_{\text{las}}) l_{\text{abs, eff}} \approx \text{const} \quad \text{until} \quad l_{\text{abs, eff}} < \mathcal{O}_{\text{target}} \]

\[ \frac{I_{\text{abs}}}{I_0} \approx 0.5 \] seems to be the highest attainable value.
General summary

To date, the obtained conversion efficiency at $\lambda = 11.4$ nm is

\[ CE \approx 2.5\%, \]

CE close to 5% seems to be attainable, provided that some optimization steps will be undertaken:

- a thorough selection of the experimental conditions so that the radiation maximum be at $\lambda = 11.2$ nm;
- optical scheme of the target irradiation should make provision for both creating a hot, EUV-emitting plasma core and heating the jet periphery to make the latter transparent for EUV quanta;
- recuperation, return of the unabsorbed laser radiation back to the plasma.

Publications:

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