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Debris –free, droplet laser plasma sources in the EUV and soft X-ray ranges

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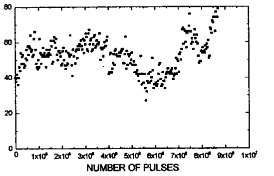
Laser plasma short wavelength sources are finding increasing applications in science and advanced technologies. In the development of Extreme Ultraviolet Lithography (EUVL), the leading technology to replace optical lithography, the source of choice is a high repetition-rate (> 1kHz) laser-plasma, capable of providing at least 7 W of radiation within a 3% spectral bandwidth at 13 nm Laser plasmas make excellent pulsed x-ray sources in the so-called "water window" (2.5 – 4 5 nm) for nanometer-resolution x-ray microscopy of biological organisms in their natural state. And plasmas produced by femtosecond lasers are now a source of high-energy x-ray radiation for x-ray diffraction and radiography. A common requirement of these applications, that there be no collateral particulate emission from the plasma, has lead to the development of the liquid droplet source, introduced in 1993[1], as a bright source in the soft x-rays and EUV radiation. Our previous work with a 100 kHz water droplet system generated 13 nm and 11 6 nm line emission from a Li-like Oxygen plasma produced by 10 ns duration, 10 Hz Nd:YAG laser pulses at ~ 10^{12} W/cm^2.



We now present a detailed quantitative study of this source, performed with a 100 Hz laser, that characterizes the radiation efficiency and the long-term operation. The results show that the droplet laser plasma source comes close to satisfying all the near-term needs of EUVL In particular we demonstrate an overall conversion efficiency of laser light to 13 nm emission within the required spectral bandwidth in excess of 0 6%, comparable to any other existing source at this wavelength. In addition we have performed an exhaustive examination of the long-term effects of plasma emissions on the reflectivity of multi-layer mirrors, exposed to this source. This included detailed surface science studies of the multi-layer mirrors after EUV radiation doses approaching those anticipated in a first generation exposure tool. This study has lead to the development of novel techniques that extend debris-free operation of this source by over an order of magnitude to close to that needed for long-term, continuous use, [10^{10} shots], at 1 kHz. The figure shows the results of a lifetime measurement the reflectivity (arb units) of a 13 nm multi-layer EUV mirror, situated 3 4 cm from the source, verifying EUVL operating conditions for > 10^9shots (the fluctuations are due to systematic droplet size variations)

In a separate study we have developed an adaptation of the droplet source for the generation of soft x-rays, from targets that contain Zn, Cu and other high-Z materials. Plasmas created from these targets by laser intensities in the 10^{12}-10^{14} W/cm^2 range will provide a debris-free source across a rich range of wavelengths. Moreover, the use of a mass-limited target permits a detailed quantitative understanding of the radiation and kinetic energetics of these plasmas to be made. We will report x-ray spectroscopic data, and discuss new applications of these new debris-free x-ray sources

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12.00 QMD5

Laser Operation with Two Controlled Transverse Modes

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In a laser resonator operating with many transverse modes, the emerging output beam quality is relatively poor. Improvement of the beam quality is typically obtained by inserting an aperture inside the resonator so as to reduce the effective radius of the gain medium, until only the optimal fundamental mode of Gaussian shape exists. Unfortunately, this results in a significant reduction of the output power. It is possible to operate a laser with a single high-order transverse mode by applying intra-cavity elements, such as apertures or phase elements [1,2]. Such high-order modes exploit a relatively large volume of the gain medium, so the output power is relatively high. However, the intensity distribution of a single high-order mode usually consists of some low-intensity regions, resulting in inefficient utilization of the gain medium, with respect to the multi-mode operation.

Here we demonstrate a novel resonator configuration in which it is possible to select two different transverse modes, each of which has a specific polarization, and can be manipulated separately. The intensity distributions of these modes can be chosen to be complementary, i.e. the peaks of the first mode would fall on the valleys of the second mode. Thus, the gain medium can be exploited more efficiently. This results in an increase in the total output power, yet with better beam quality than with the multi-mode operation.

A representative resonator configuration, for a laser operation with the fundamental TEM_{00} mode (selected with an aperture) and the Laguerre-Gaussian TEM_{02} mode (selected with a discontinuous phase element – DPE) is shown in Fig. 1. Here, we insert a polarizing beam splitter (PBS) into the resonator, so as to form two different paths for the two orthogonal polarizations. These two paths coincide inside the gain medium, but have different paths near the output coupler, where an intra-cavity mode-selecting element, such as an aperture or a phase element, is placed. The emerging beams may be united with external elements, to obtain a single beam of high quality and relatively high power.

We tested such a resonator configuration in a Nd:YAG laser. The results are shown in Fig. 2. Figure 2(a) shows the near-field intensity distributions for each of the two modes and Fig. 2(b) the corresponding far field intensity distributions, where the high central peak is evident. The combined output power was 5.6W, compared to 3.2W of the single fundamental mode and 4.7W of the single high order TEM_{02} mode.

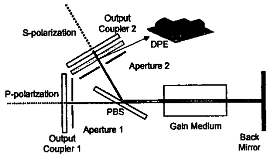

Fig 1: Resonator configuration

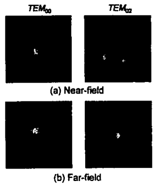

Fig. 2: Output beam intensity distribution

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