Development in Gas-Discharge Drive Lasers for LPP EUV Sources

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ABSTRACT

Development of a drive laser with sufficient output power, high beam quality, and economical cost of consumables is critical to the successful implementation of a laser-produced plasma (LPP) EUV source for HVM applications. Cymer has conducted research on a number of solutions to this critical need. We report our progress on development of a high power system using two gas-discharge power amplifiers and repetition rates exceeding 10 kHz to produce more than 2kW output power with high beam quality. We provide optical performance data and design features of the drive laser as well as a path to output power scaling to meet high volume manufacturing requirements

Keywords: pulse laser, gas discharge laser, XeF power amplifier, laser-produced plasma, EUV

1. INTRODUCTION

Development of Drive Laser for LPP EUV source is a challenging task. It requires a multi-kW laser output with short pulse duration and diffraction limited beam quality [1]. In addition, this system has to be very reliable and cost efficient to satisfy industrial requirements for high volume integrated circuit manufacturing. In this publication we report on feasibility studies of the high power laser system that utilizes proven excimer laser technology in high-power optical gain modules and delivers required beam properties.

The top-level target specification of the drive laser system is shown in Table 1. Operating at 351 nm, this system is targeted for 2400 W average power output with electrical-to-optical conversion efficiency close to 4%.

Table 1
Target top level optical specifications for 351nm Drive Laser

Parameter	*value*
Wavelength	**351 nm**
Power	**2400 W**
Pulse energy	**200 mJ**
Repetition rate	**12 kHz**
Pulse duration	**~10ns**
Beam divergence, 90% encircled integral	**200 μRad**
Beam pointing	**25 μRad**
Energy dose stability, 100p.-window	**0.3 %**
Laser efficiency	**4%**

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2. CONCEPT

A novel proposed concept of the drive laser system for LPP EUV source is illustrated in Figure 1. A single frame two-channel hybrid system utilizes Cymer's XLA MOPA universal platform. Two gas discharge excimer gain modules are seeded by the high repetition rate solid-state master oscillator (MO). The two-channel approach allows high repetition rate operation while the gas flow limited gain modules operate at half the repetition rate of the MO. The optical architecture of the system can utilize master oscillator-power amplifier (MOPA) or master oscillator-power oscillator (MOPO) configurations.

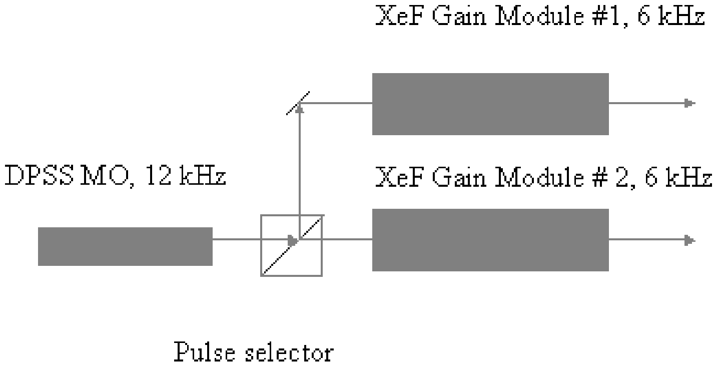

Figure 1. Concept of the hybrid drive laser system for LPP EUV source: MO is a high beam quality; high repetition rate diode pumped laser. The MO operates at doubled repetition rate to seed XeF power gain modules in alternating sequence through the pulse selector.

One of the advantages of the proposed system is that it uses very robust, high power XeF gain modules, developed on proven excimer laser technology. Another advantage of the system is that it implements a cost efficient diode pumped MO with diffraction limited beam quality [2]. The MO laser is a frequency tripled Nd:YLF laser, operating at 351 nm wavelength. Commercially available 3rd harmonic Nd:YLF lasers, are capable to operate at high repetition rates exceeding 10 kHz [3] and deliver near diffraction limited beam quality with M^2 parameter close to 1.

3. AMPLIFICATION OF 3RD HARMONIC Nd:YLF PULSES IN XeF GAIN MODULE

As a first step we performed feasibility studies on the amplification of the laser beam produced by the commercially available 3rd harmonic Nd:YLF laser in the XeF gas discharge gain module. In these experiments we used a production-grade excimer laser chamber. The chamber was filled with a Xe:F_2:Ne gas mixture and was excited by using a production-grade pulse power module from the ELS 6010 series. A commercial Q-switched diode pumped 3rd harmonic Nd:YLF laser form Photonics Industries International (model DS10-351) was used as MO. The pulse synchronization between the solid-state MO and the gain module was provided using a Stanford delay generator (DG-535). The output beam from the MO was expanded in the vertical direction with the help of a prism beam expander to match the cross-section for the discharge of the gain module. A single-pass PA optical configuration was set up.

The spectroscopic measurements of Amplified Spontaneous Emission (ASE) in 351-353nm range are shown in Figure 2. The energy of ASE pulses was approximately 30 mJ, indicating that the spectrum in the Figure 2 corresponds to the gain saturated condition. There are three strong ASE lines, associated with the 351.1

nm (ν=1-4), 351.2nm (ν=0-2), and 353.2nm (ν=0-3) transitions within the B-X XeF manifold of the XeF molecule. This observation is in a good agreement with spectroscopic data on XeF [4,5].

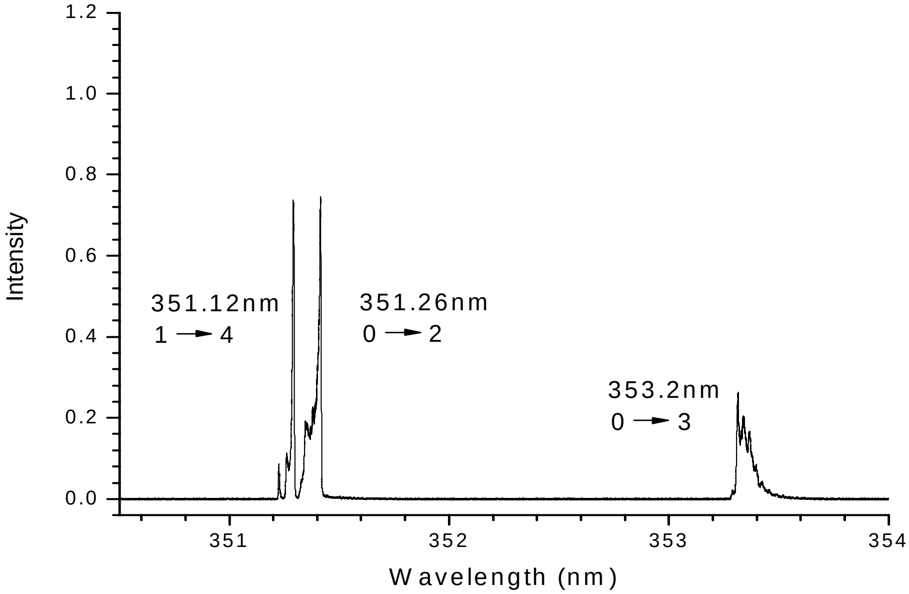

Figure 2. ASE spectrum, measured at the output of XeF gain module. Each data point of the spectrum is an average of 3 acquisitions; CCD exposure time is 600ms. The XeF gain module was operated at 100Hz.

Figure 3 shows three spectra: the MOPA output spectrum, the spectrum of the solid state MO acquired through the PA module; and the ASE spectrum, taken when the MO beam was blocked. The spectral bandwidth of the "free running" 3rd harmonic Nd:YLF MO is approximately 40 pm wide (FWHM) and the central wavelength is shifted to the shorter wavelength region in respect with the PA ASE spectrum. The ASE spectrum of PA barely overlaps with the tail of the MO spectrum. There is a dramatic difference between the ASE spectrum and the MOPA output spectrum (via single-pass amplification of MO beam in PA). Due to the high gain values in XeF media, even a very small fraction of MO energy, contained in the overlapping parts of the MO and PA spectra is strongly amplified by XeF gain generator. As a result, the energy extraction from the PA occurred mostly on the weak lines on the shorter wavelength side of the spectrum. In particular, a weak 351.08nm line, barely traceable in the ASE spectrum, becomes amplified approximately 100 times in a single pass PA. To extract more energy from the strong 351nm XeF emission lines and to provide better PA efficiency, the MO output needs better spectral overlap with the XeF gain lines. In accordance with the other studies [5], at least two emission lines of the XeF gain need to be seeded for sufficient energy extraction. The 1053 nm fluorescence line of Nd:YLF crystal is approximately 1.5 nm wide[6], making it feasible to seed both XeF lines, centered at 351.12nm and 351.24nm with one 3rd harmonic Nd:YLF source. The first experimental results on the tunability of the 3rd harmonic Nd:YLF laser are shown in Figure 4. These results demonstrate stable operation of the 3rd harmonic Nd:YLF laser output with wavelength tuned to match the 351.12nm line.

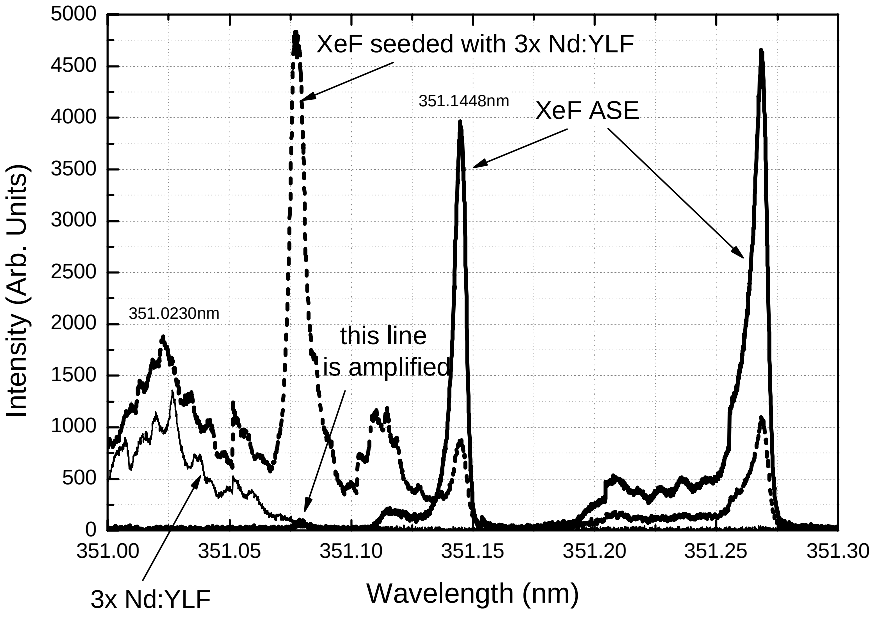

Figure 3. Spectral measurements on MOPA set up, 1-pass PA:

1. Q-switched 3^{rd} harmonic Nd:YLF MO spectrum measured at PA (XeF gain module) output
2. ASE output measured at PA output (MO blocked)
3. Single pass PA output, seeded by the Q-switched 3^{rd} harmonic Nd:YLF MO.

MO pulse energy: ~1mJ; MO pulse duration ~50ns (FWHM)

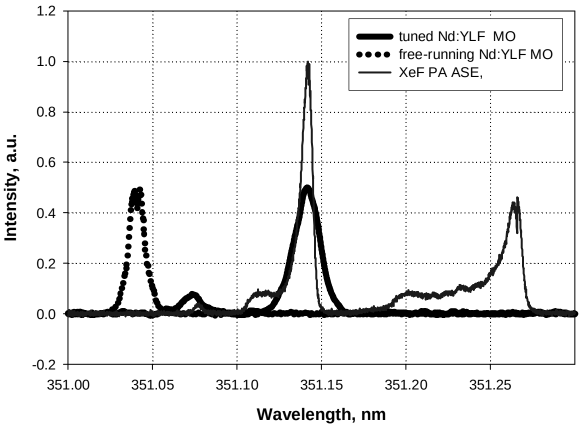

Figure 4. Demonstration of wavelength tunability of the 3^{rd} harmonic Nd:YLF MO to match XeF XeF gain line at 351.12nm. The bandwidth of 1053 nm Nd:YLF fluorescence line is sufficient to seed also the 351.25 nm line of XeF.

4. ENERGY REQUIREMENTS FOR MO INPUT ENERGY USING VARIOUS PA CONFIGURATIONS

In order to extract maximum energy, the gain module has to be operated in a gain saturation regime. The requirement for MO energy to induce the gain saturation depends on the specific configuration of PA optical system. In practical systems such a dependency often limits the choice of the possible PA configuration. As a first step in defining the optical architecture of the drive laser we studied the relation between the MO energy and the MO-PA energy for three different PA optical configurations: single-pass, double-pass, and triple-pass. In these experiments, we used two XeF gain modules, functioning as MO and PA modules. The MO cavity was formed by a flat mirror and by a 20% flat output coupler. The amount of MO energy coupled into PA was adjusted with an external optical attenuator. MO and PA charging voltages were kept constant throughout the measurements in order to keep the discharge characteristics the same. The PA efficiency curves and PA and MOPA energies are shown in Figure 5.

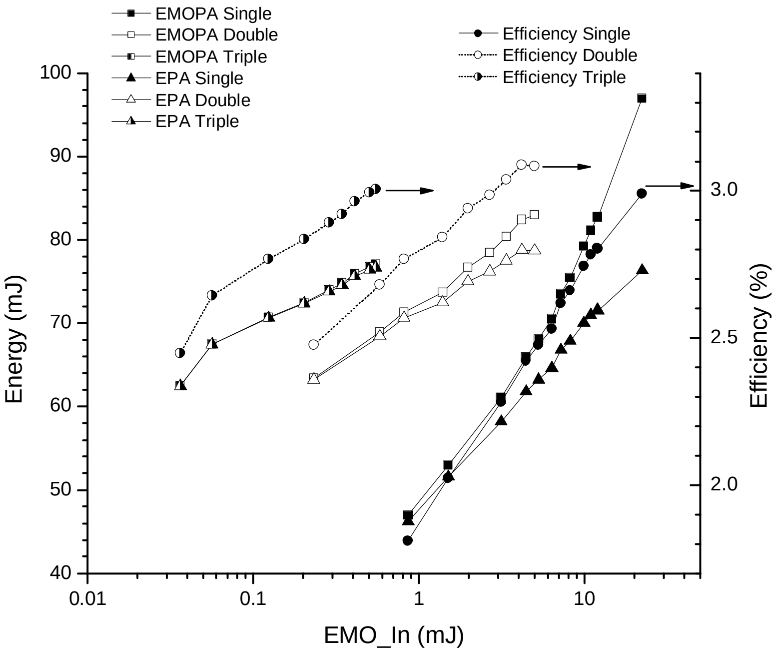

Figure 5. MOPA and PA output energy, and PA extraction efficiency versus MO energy (EMO_In) for various optical configurations for PAs; repetition rate is 100Hz. The MO and PA chambers in this experiment are similar to the chamber used in experiments described in Section 3.

The extraction efficiency of the PAs was calculated as (E_{MOPA}-$E_{MO\_through}$)/Eco*100%, where E_{MOPA} is the MOPA output pulse energy, $E_{MO\_through}$ is the MO pulse energy measured at the MOPA output with no electric discharge in PA section; Eco is the electric charge energy of the first stage capacitor in the multi-stage pulse power module [7]. The actual electric-to-optics efficiency of the gain sections is higher due to losses in the pulse power modules.

The maximum PA energy extracted in these measurements, E_{PA}, was ~ 76mJ and the maximum extraction efficiency of ~3% was achieved for all three PA configurations. However, the single-pass and dual-pass PA configurations require much higher E_{MO} to provide similar energy performance and extraction efficiency as the triple-pass configuration. Only about 0.5mJ of E_{MO} is required for the triple-pass PA to achieve similar

MOPA performance as with the dual-pass PA, seeded with about 4.0mJ of E_{MO}. In the case of the single-pass PA, about 20mJ of E_{MO} is required for comparable energy performance. The highest E_{MOPA} ~97mJ was demonstrated in a single-pass PA configuration , which is not surprising due to the high E_{MO} values required for efficient operation.

5. ENERGY REQUIREMENTS FOR MO INPUT ENERGY FOR MOPO CONFIGURATION

The number of passes in the gain module can not be significantly increased above a triple-pass PA scheme due to physical constraints of the system. Therefore, about 2 mJ of MO pulse energy is needed for practical MOPA design. The use of Master Oscillator Power Oscillator (MO-PO) approach offers another method for further reduction of MO pulse energy. The experimental set up of the MOPO configuration is shown in Figure 6. The MO and PO XeF gain modules were based on the same gas discharge chamber technology as the MOPA configurations described above. The MO cavity was identical to the set up used in previous MOPA experiments. A spatial filter was used to improve beam quality of the MO output.

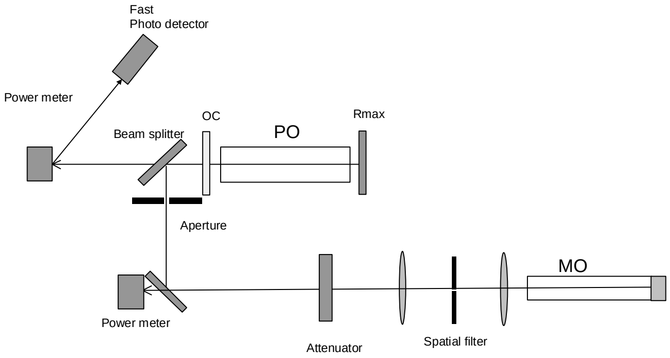

Fig. 6. MOPO set up, featured XeF master oscillator, XeF power amplifier and the pulse energy diagnostics.

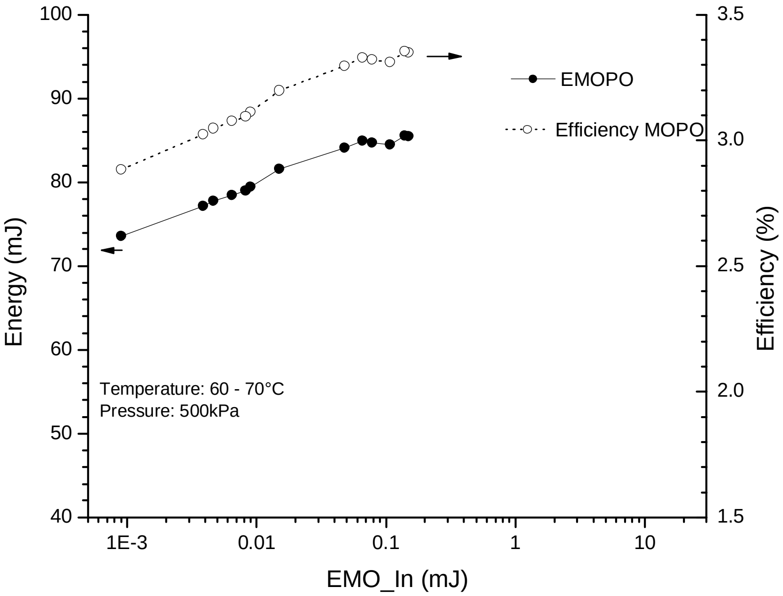

Figure 7. MOPO output energy and PA extraction efficiency as a function of MO energy.

The spatial filter was formed by a small aperture placed in a focal plate of the telescope, consisting of two spherical lenses. After the spatial filter, an optical attenuator was used to adjust the amount of MO energy injected into the PO cavity. Before the MO beam was injected into the PO cavity it was directed through an aperture and shaped to match the PO discharge cross section. The coupling of MO beam into PO resonator was done through a partial reflector. Optical isolation between MO and PO was achieved by introducing a long optical delay between MO and PO. The MO energy was measured before the PO output coupler; The MOPO energy was measured after the beam splitter and corrected for the beam splitter transmittance.

The maximum PO energy extracted was ~ 82 mJ which is comparable with the MOPA results presented in Section 4. The maximum extraction efficiency was ~ 3.4%, which is higher compared to the MOPA results An important advantage of the MOPO system is that it requires much lower MO energy compared to the MOPA configurations.

6. PULSE DURATION

A comparative evaluation of the temporal pulse shape at the output of MOPA for single- and triple-pass PA configurations, as well as at the output of MOPO was done. The gas discharge chambers used for the MO and PO modules were similar to the modules used in Section 3, 4, 5. A Hamamatsu vacuum phototube (R1328U-52) with < 270 ps rise time was used for time resolved measurements. The phototube signal was acquired with a 500MHz Tektronix oscilloscope (TDS-640A). Pulse waveforms for the MOPA and MOPO configurations are shown in Figure 8.

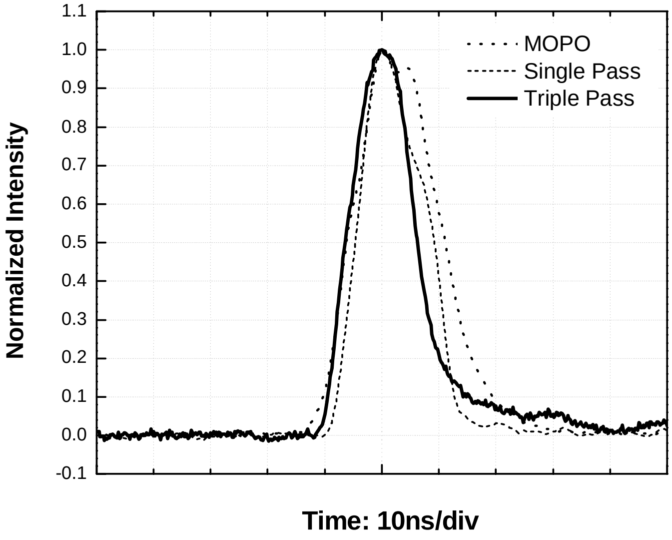

Figure. 8. Temporal pulse shapes for three configurations: MOPO, MOPA $_{1\text{-pass}}$ and MOPA $_{3\text{-pass}}$. Pulse width values (τ) measured @ FWHM: τ_{MOPO}~17.3ns, τ_{MOPA}1pass~13.9ns, τ_{MOPA}3pass ~12.7ns. The measurements were performed at optimal trigger delay between MO and PA(PO) modules, corresponded to maximum output energy [7].

A comparison between the MOPA and MOPO pulse shapes shows that the shortest pulse duration is generated with a triple pass PA configuration. Approximately 1ns difference is observed in the pulse width (FWHM) for the single-pass and triple-pass PAs. The longest pulse width is generated by the MOPO set up. This result is consistent with the pulse width data reported for the line narrowed MOPA and MOPO ArF systems [8]. If necessary, a reduction of the pulse width can be achieved by reducing the gas discharge duration.

7. PROGRESS IN DEVELOPMENT OF HIGH POWER XeF GAIN MODULES

Significant progress has been achieved in the technology development of XeF gain modules. The key challenge for the discharge chamber is meeting the high average power requirement. The core chamber technology used in Cymer's XLA systems proved to work reliably at 4kHz, 100% DC, producing an average power of ~400W per module (see Figure 9) for many hours. In order to achieve the 1200W system power requirement the pulse repetition rate will be increased to 6kHz and the pulse energy will be increased to ~200mJ. Figure 10 illustrates the progress made toward these goals. The left-hand graph shows improvements in gas flow technology that achieve a 40% reduction in the motor power required for the maximum flow speeds. This technology is a key to achieving 6kHz in a chamber that is the same size as the XLA 4kHz chamber. The right-hand graph demonstrates improvements in energy extraction. A 34% increase in energy extraction has already been demonstrated.

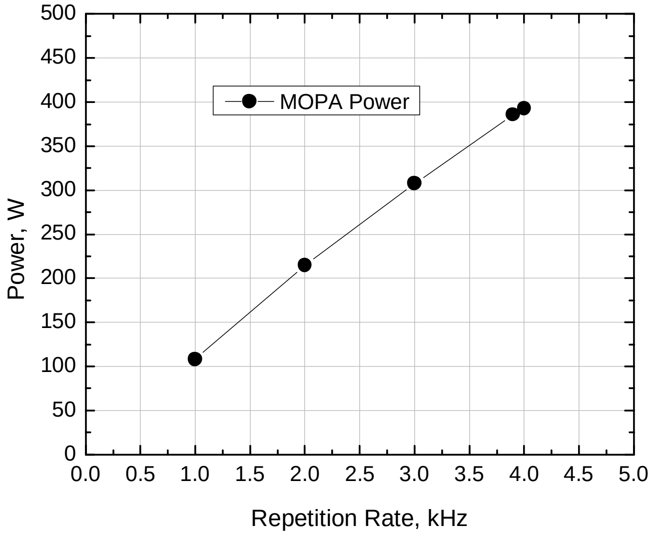

Figure 9. Single-pass MOPA output as a function of repetition rate; measured at 100%DC. Details of the MOPA system are described in Section 8.

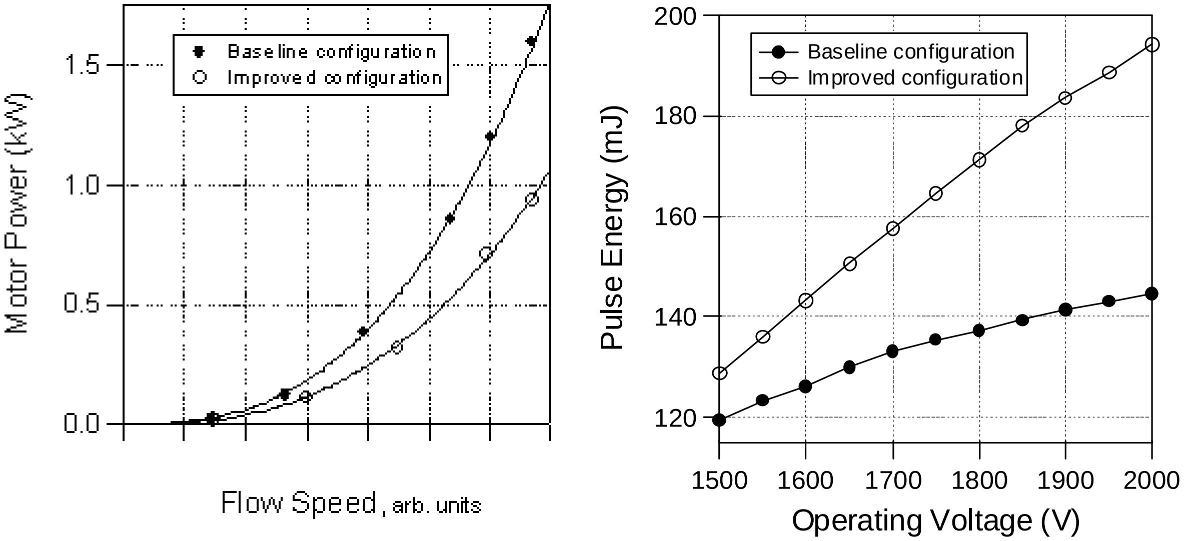

Figure 10. Progress on XeF chamber development towards 1200W average power operation: Flow improvements required for 6kHz are shown on the left and improved energy extraction required for 200mJ per pulse are shown on the right.

8. LONG-TERM PERFORMANCE OF XeF GAIN MODULES

The gas lifetime in XeF gain modules is expected to be similar or longer than in KrF gain modules, manufactured by Cymer, Inc. We expect a pulse count of at least $2*10^8$ during the active gas lifetime and at least 5 days for the maximum re-fill interval as a passive gas lifetime requirement. The drive laser gain modules will use a new algorithm for the gas injects that will allow maintaining the optimal concentration of F_2 and Xe in the chambers.

An example of a 200 million pulses run, performed on specially developed high repetition rate XeF MOPA system with a single-pass PA, is shown in Figure 11. This new MOPA system built for reliability tests uses production-grade 4kHz chambers, similar to the chambers in the ELS-7010 DUV products. It operates at 100%DC, producing up to 800W of the output power. During the gas lifetime test the system was generating 150mJ output pulses at 4kHz, 100%DC. A simple pulse-count based gas inject algorithm was implemented to maintain the operating voltage within required range.

There were four negative spikes of the MOPA output observed during the run associated with operation at maximum voltage. The first spike occurred at ~80M pulse count right after the stand-by mode. It was fixed through the alignment of PA optics. Three other negative spikes are associated with F_2 depletion in the gas mixture. Implementation of a more sophisticated gas inject algorithm will allow in the future to reduce the fluctuation of the operating voltage and to increase the gas lifetime of the gain modules.

Multiple 200M shot runs in 600-800W power range were continued to test the most critical modules of the MOPA system. Currently, the total pulse count on the system approaches 10^{10} pulses. During this test, the pulse energy density and average power density on output optical components exceeded 0.5J/cm^2 and 1.7kW/cm^2 levels. There were no failures observed neither on reflective nor transmissive optical components. Currently investigations on optics lifetime at higher energy density and power density levels are underway.

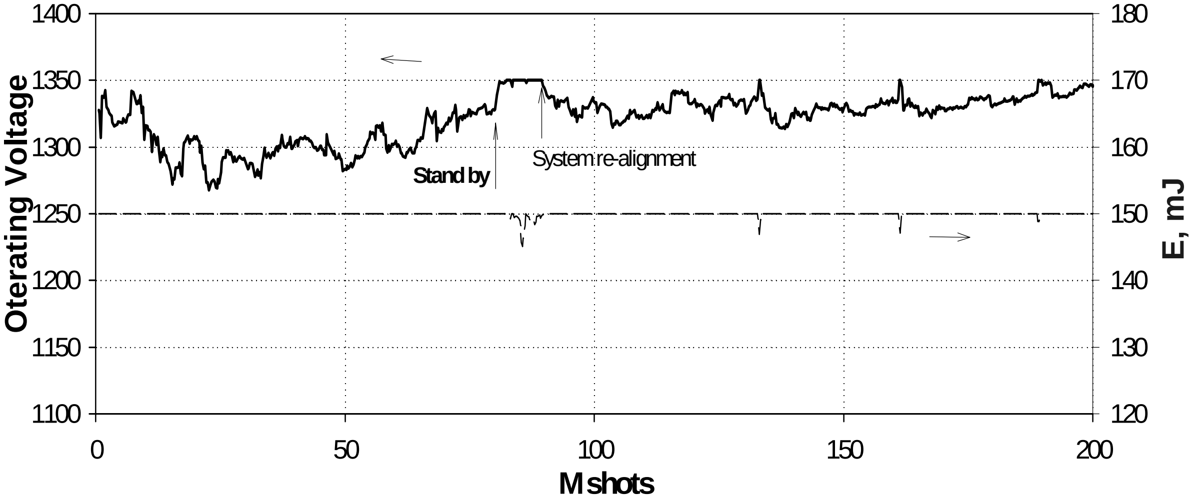

Figure 11. Example of a 200M shots gas run performed at constant energy mode, average power was set to 600W. A shot count-based gas auto-inject algorithm was used to compensate for the active gas consumption. The operating voltage in this test was limited by 1350V. The nominal operating range of the system is 1000-1500V.

9. SUMMARY

In this paper, a concept of a 351nm drive laser system for LPP EUV source is described. The proposed drive laser system is based on two XeF Power Amplifiers driven by a single, high beam quality 3rd harmonic Nd:YLF master oscillator. Feasibility studies on amplification of the 3rd harmonic Nd:YLF laser beam in a XeF power amplifier demonstrated the tunability of the solid-state laser to match one of the strong lines of the XeF gain spectrum. Two basic architectural approaches, namely, MOPA and MOPO systems, were evaluated using the XeF gain modules, developed at Cymer, Inc. It was shown that both XeF MOPA and XeF MOPO configurations are capable to deliver optical performance required for LPP EUV source. The advantage of MOPO system is that it has low requirements on the MO pulse energy, < 30 µJ. The MOPA configuration requires higher energy of the MO pulses. However, it provides better flexibility for beam quality optimization and deliver pulses with shorter duration. Reliable operation of the MOPA system, over ~10^{10} pulses at 600~800W output power, showed no critical optics damage issues. The key performance characteristics achieved using combinations of the high beam quality XeF MO with the high power XeF PO and XeF PA modules are summarized in Table 2.

Table 2

Summary of demonstrated optical performance

Parameter	*Current Performance*
Power	**800W**
Beam Quality	**<150 μRad**
Energy Stability (30pulse)	**1%**
Repetition Rate	**4000 Hz**
Efficiency	**3.50%**
Pulse Length	**<16ns**
Pointing Stability	**<25uRad**

Future development of the Drive Laser will include optimization of the beam quality, extension of the operating repetition rates to 8 kHz, increase of output energy and power and system efficiency.

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