Long-term Reliable Operation of a MOPA-based ArF Light Source for Microlithography

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ABSTRACT

Since the introduction of the XLA-100 in January 2003, we have built, tested, and shipped a large number of XLA-100 MOPA lasers to microlithography scanner manufacturers. Some systems have already been installed at chip fabrication lines. To ensure product design robustness, we have been performing a long-term system performance test of an XLA-100 laser at Cymer. In this paper, we will report optical performance of the XLA-100 we see during manufacturing final tests, and a summary of the long term testing.

Keywords: Excimer laser, 193nm light source, narrow bandwidth, MOPA, DUV, Microlithography

INTRODUCTION

The XLA-100 is a master oscillator and power amplifier (MOPA) based ArF excimer laser for microlithography. The XLA-100 has demonstrated performance and stability that were unattainable by the traditional single oscillator line-narrowed laser design. The MOPA design uses two discharge chambers. The master oscillator (MO) generates an extremely line-narrowed ArF laser beam with a relatively small energy content, typically 1mJ. The power amplifier (PA) amplifies the laser pulse from the MO. The beam from the MO traverses the amplifier’s gain region while making one round trip. The output from the PA is horizontally expanded to produce a 12x12 square beam using an anamorphic beam expander. It is then stretched temporally to increase pulse duration to longer than 44nsec measured as the Time Integral Square. The XLA-100 employs an optical delay line to handle this task. Spatially larger and temporally longer laser pulses reduce the maximum photon flux density to which the scanner optics are exposed. A detailed discussion of the XLA-100 design was presented in previous papers.[1, 2]

A summary of the XLA-100 key optical performance and expected lifetimes is presented in the table below.

Parameter	**Value**
Average Output Power	40W
Maximum repetition rate	4kHz
Energy Dose stability (20ms window)	< 0.3%
Operational Pulse Energy	8.5 - 11.5mJ
Peak energy density	< 30mJ/cm^2
Temporal pulse width (Integral Square definition)	>44ns
Wavelength Tuning Range	193.200nm – 193.500nm
Spectral Bandwidth, FWHM	< 0.25pm
Spectral Bandwidth, E95%	< 0.65pm
Short term Wavelength stability (20ms window)	< ± 20fm
Gas life	100M shots, 72 hours
Chambers	PA 16Bpulses, MO 12Bpulses
LNM	12Bpulses
LAM and SAM	20Bpulses

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The extremely narrow output spectrum of the XLA-100 enables scanners with an NA greater than 0.9. Higher average output power improves the wafer throughput of the scanner. In addition, extended lifetimes of discharge chambers help to control the operating cost. Variable energy and repetition rate capabilities provide scanners with a freedom to use the optimum laser operating modes for any processes, thus always ensuring the best results.

PRODUCTION LASER PERFORMANCE

The key parameters that determine a laser's conformance to the photolithography tool light source requirements include spectral bandwidth, wavelength stability, energy stability, and near and far field beam profiles. In manufacturing, the XLA-100 lasers go through sets of tests that are designed to characterize and evaluate the performance of each laser to the specifications. The first set of tests run the laser in various operating modes, which check to see how the laser runs in operating modes that represent actual wafer exposure processes. In some tests, multiple parameters are simultaneously measured, and in others a single performance parameter is carefully analyzed. The second set is a gas test. Every production laser goes through an optical parameters and system stability test of 100Mpusles. Typically, three operating modes with different duty cycles are tested including some long pauses for the total pulse count of a minimum of 100Mpulses. The gas test monitors and evaluates optical performance stability in both the short and long term.

Over the gas lifetime of 100Mpulses, the XLA-100 maintains an excellent stability. Fig. 1 shows high voltage (HV) and master oscillator output energy (MO Energy) recorded during a gas test. The changes in HV and MO Energy seen in Fig.1 are mostly due to duty cycle change, rep rate changes, and fluorine gas injections. Minor periodic drops in HV and MO Energy are due to F2 injections while more gradual or larger changes are due to operating mode changes.

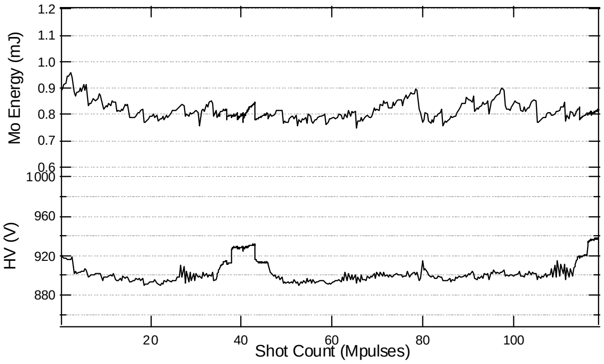

Fig.1: Average high voltage and MO energy recorded over 120Mpulses. Data were acquired every two minutes and averaged over 3000pulses.

The fluorine gas control scheme specifically designed for a simultaneous control of the fluorine concentrations of the MO and PA chambers tightly holds the MO and PA F2 concentrations in a good balance. The MO energy and the high voltage are maintained within the ranges that are required for stable optical performance by individually adjusting the amounts of fluorine gas injected into the two chambers. During the gas test shown in Fig.1, the HV was maintained within a 40V range, and the MO Energy was kept between 0.75 and 1mJ. Actual HV and MO Energy ranges depend on the exact condition of laser, and may vary. The new fluorine control algorithm is capable of estimating desirable ranges as the chamber efficiencies change, and thus makes it possible for the XLA-100 to provide an excellent stability from one gas fill to another.

To analyze the laser's spectral purity, high-resolution grating spectrometers are used in our manufacturing test labs. All lasers are characterized by the Elias II spectrometer which has a resolution of 0.02pm or better. The laser spectral profiles measured by the spectrometer are processed using a FFT-based deconvolution routine that accurately removes effects of the spectrometer instrument function. Then, the FWHM and E95 bandwidth values are calculated from the deconvolved spectral profiles.

Fig.2 shows a stable spectral bandwidth performance over the gas life. Some small but sudden jumps coincide with mode changes. The E95 bandwidth shows a minor increasing trend, which is a chamber gas age effect. Duty cycle effects on the bandwidth are due to a combination of the thermal loading to line-narrowing optics and the temporal changes in laser gain formation. The XLA-100 line-narrowing module employs a mechanism that always keeps in a relaxed position a key optical element that affects the wavefront curvature of the laser light incident on the high dispersion grating, and as a result minimizes the thermal effect on the laser spectrum bandwidth. Fig.3 is a histogram of the spectral bandwidth measurements from 60 production lasers taken during the gas test.

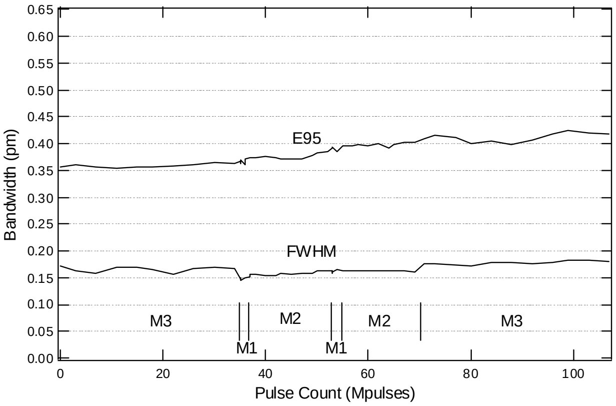

Fig. 2: FWHM and E95 bandwidth monitored over 100Mpulses. Vertical lines indicate mode changes. M3: 75% duty cycle, M2: 29% duty cycle, M1: 9% duty cycle.

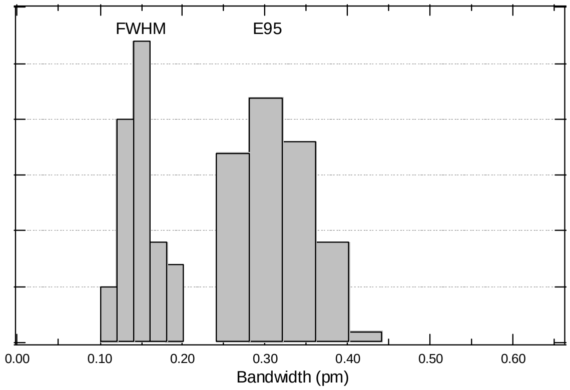

Fig.3: Histogram of the maximum FWHM and E95 recorded during gas test for 60 production lasers.

Short-term wavelength stability is strongly affected by the motion of the reflective mirror inside the line-narrowing module. Strong vibration sources that may cause the mirror to oscillate are set to operate outside of the mirror's resonance frequency bands so that it does not make large oscillations that in turn manifest in unacceptable wavelength oscillations. Also, certain fast changes in the reflective index of the laser gas, which are caused by thermal changes and acoustic waves, result in wavelength burst transients that also degrade the short-term wavelength stability. The XLA-100 wavelength control can timely react to those transients. On the other hand, the long-term wavelength stability is determined by the stability of the wavelength monitoring tool.

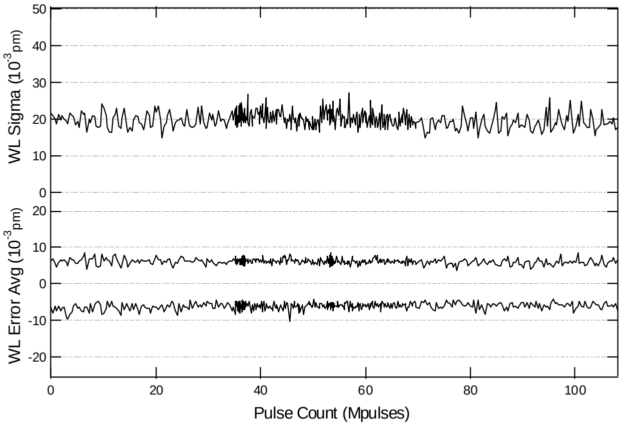

Fig. 4: Wavelength error average and sigma measured over 100Mpulses. A 30-pulses window was used for these calculations.

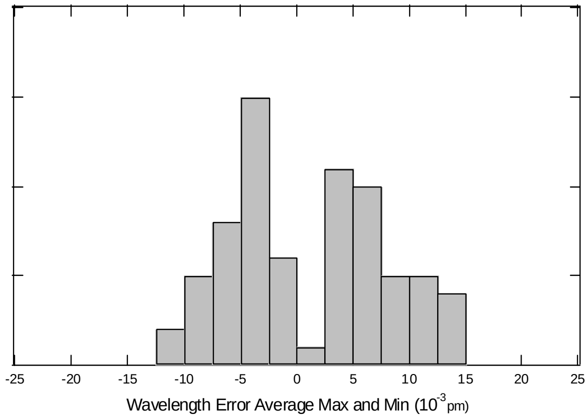

Fig.5: Histogram of the maximum and minimum wavelength error averages monitored over the gas life for production lasers.

Two figures shown above are for short term wavelength stability. Fig.4 shows short term wavelength stability recorded during a gas test. Wavelength stability data points are captured every two minutes during the manufacturing gas test. Both wavelength error average max and min, and standard deviation are well below the specifications. The wavelength error average is kept within ± 10fm, and the standard deviation is less than 30fm. Fig.5 is a histogram of wavelength stability from production lasers taken during the gas test.

The XLA-100 employs an optical pulse stretcher to increase pulse duration and thus reduces the laser peak power density. Fig.6 is a typical gas test result, and in Fig.7 the mean minimum TIS for production lasers is 50nsec.

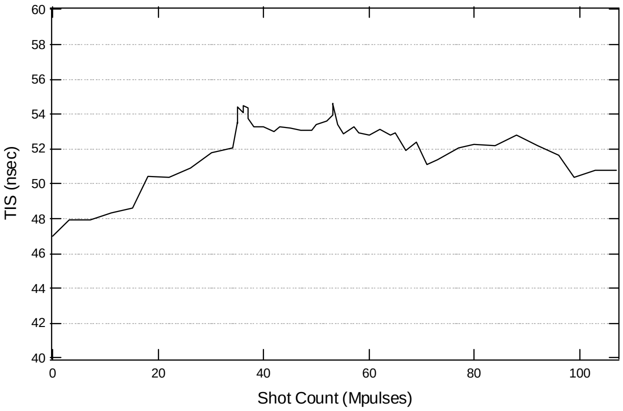

Fig. 6: TIS pulse duration monitored over 100Mpulse.

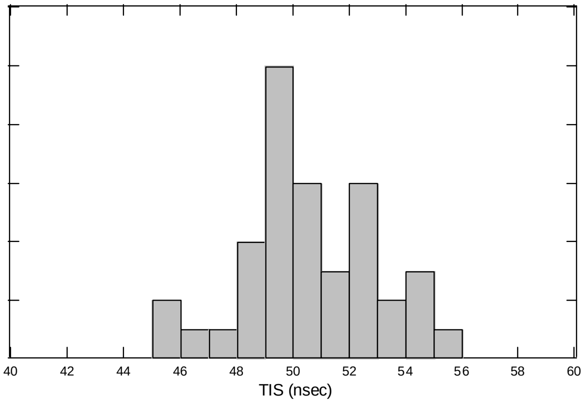

Fig.7: Histogram of TIS pulse duration for production lasers.

LONG TERM SYSTEM PERFORMANCE

The XLA-100 lifetest, which is designed to characterize long term stability of the optical performance and to gather system reliability data, has been running in our system reliability test laboratory. The lifetest has demonstrated stable optical performance over a large number of pulses, and at the same time identified the need for further design improvements to enhance the long term system performance and reliability. The test is based on a larger number of 100Mpulses gas tests repeated one after another. The 100Mpulses test protocols for the lifetest are very similar to the ones used in the manufacturing final gas test. At certain milestones which are set by the pulse count of the PA, a set of special tests that are designed to evaluate the optical performance in the ways different from the gas test are conducted, and a thorough system health checkup including optics inspections is also done at the same time. At the time of writing this paper, the lifetest laser registered more than 13 billion pulses.

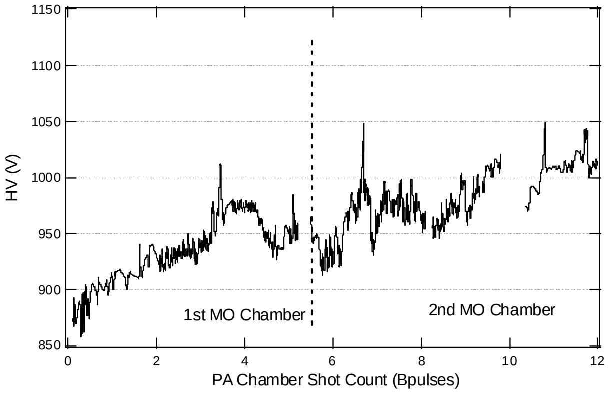

Fig. 8: Lifetest high voltage trend over 12Bpulses.
No life data were taken for the periods during which the lifetest laser was used for special tests.

The high voltage trend over 12Bpulses is shown in Fig.8. Operating voltage started near 900V, which is typical for the XLA-100 with new chambers. The first MO chamber started exhibiting degradations in lasing efficiency and pulse energy stability after 4Bpulses, and it was replaced at 5.5B with another chamber of the same design. The postmortem of the first MO chamber revealed that electrode erosions caused the degradations observed. The second MO chamber has been tested for more than 6Bpulses, and it still produces more than 0.8mJ, sufficient for a stable operation

Concurrently with the lifetest program, we had an electrode lifetime extension project as part of the on-going discharge chamber improvement program. That electrode lifetime extension project was successfully executed and has provided a new design that has shown to last more than 12Bpulses in the MO position. A design verification of the new long life chamber design was done on another frame and was completed with all optical performance parameters in spec. Performance of the newly designed longer life chamber is presented in the next section.

In comparison with the MO, the PA efficiency is much less sensitive to the electrode erosion that caused the short lifetimes of the original MO chamber design. When the lifetest PA chamber had more than 10Bpulses, it was briefly tested with a new MO chamber, and the average HV was close to 900V. Over the entire 12Bpulses, the gas fill pressure was kept at 260kPa and unchanged. The chamber pressure can go up to 380kPa if required.

Spectral bandwidth measurements done by a high resolution grating spectrometer all met specifications during the entire 12Bpulses. The FWHM bandwidth was always below 0.2pm, and the E95 bandwidth was better than 0.40pm, as shown in Fig. 9. The fact that two MO chambers were used during the 12Bpulses period indicates that the MO chamber age has only a minor effect on the spectral bandwidth.

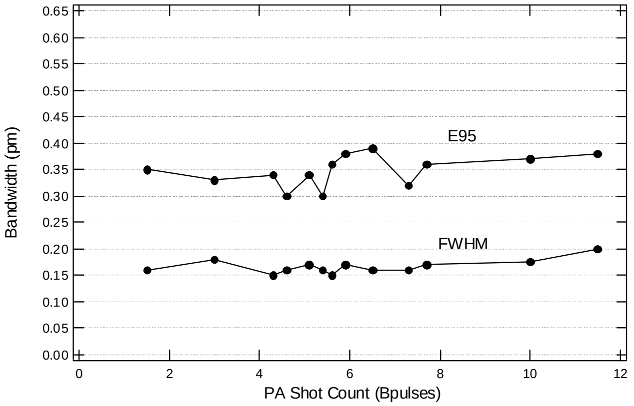

Fig. 9: FWHM and E95 bandwidth trends over 12Bpulses.

Long-term wavelength stability is measured as a slow drift in the line center analysis module calibration. For the lifetest, we occasionally run an automated wavelength calibration routine using the built-in absolute wavelength reference while disabling the auto error correction function so that the total amount of calibration drift can be recorded. In normal operation, the error correction is enabled and the calibration parameters are automatically adjusted after each wavelength calibration scan so that the laser output wavelength is always accurately measured and controlled. Fig.10 shows the long-term calibration drift observed during the lifetest. At 5B, we changed the wavelength calibration routine from a constant system energy control to a control method that is similar to the one used in our single oscillator laser models. That change greatly improved wavelength calibration repeatability, and it has been implemented in all production XLA-100 lasers. The wavelength calibration drift is so far about 2fm per billion pulses.

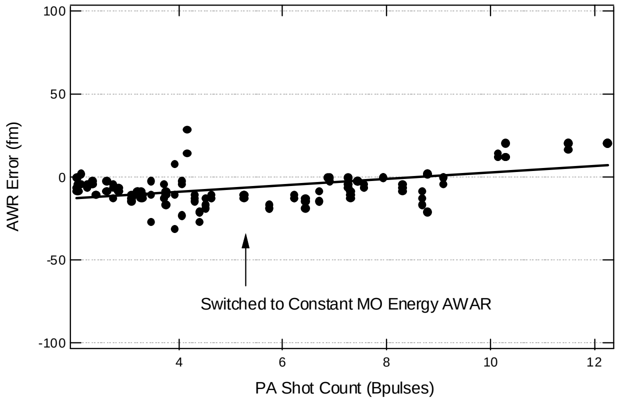

Fig. 10: Wavelength calibration error monitored over 12Bpulses.

MO CHAMBER LIFETIME IMPROVEMENT

Short discharge chamber lifetimes are typically due to the changes in laser gain profile that happen when the strong electric discharge erodes electrode surfaces. We have redesigned the XLA-100 discharge electrodes, and succeeded in controlling the gain profile more tightly and reducing the undesirable effects of electrode erosion. The new chamber design gives MO chamber lifetimes exceeding 12Bpulses.

The new long life chamber design was first tested in a single oscillator laser that was configured to be optically and electrically equivalent to the XLA-100 master oscillator. Since our main concern was its lifetime performance in the MO position, the single oscillator test was able to provide the information we needed to judge whether the new chamber design could meet the lifetime target or not without using a MOPA frame. Fig.11 shows high voltage trends over 12Bpulses for the two new long life chambers tested in the single oscillator configuration. The two chambers exhibited very similar high voltage trends, and the average operating voltages at 12B were just above 1100V. The new chamber design can operate reliably up to 1180V.

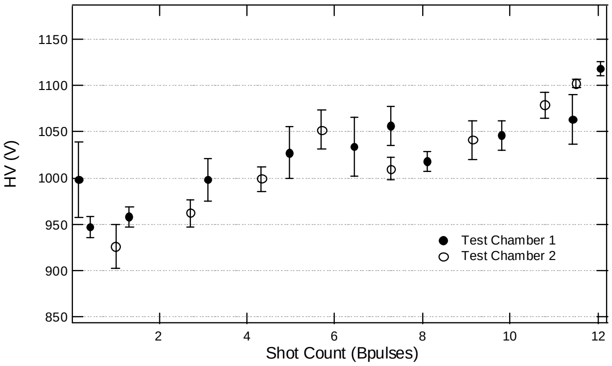

Fig.11: High voltage trends of the two chambers tested with the new electrode design in a single oscillator laser.

After completing the single oscillator test, one of the two chambers tested for 12Bpulses was installed as the MO chamber in an XLA-100 laser, and its performance was tested. Energy vs HV curves for the system and MO energy outputs in 4000Hz operations are shown in Fig.12. The system needed 1000 – 1020V to produce10mJ output pulses. The MO output energy reached almost 2.5mJ at 1150V, and the system output energy had a more than 40% overhead, which ensures proper operations even at the 11.5mJ output level.

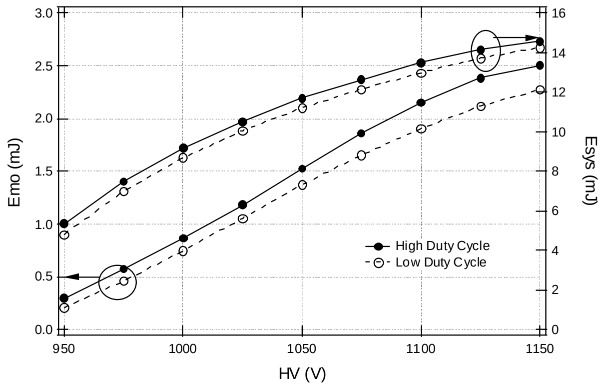

Fig. 12: MOPA System and MO energy outputs vs HV.
A 12Bpulses old chamber was used in the MO position.

The XLA-100 is designed to operate from 1500Hz to 4000Hz. Resonance scans are used to check optical performance over the entire operational repetition rate range. As shown in Fig.13, the FWHM bandwidth was below 0.2pm even at the peaks of the resonance curves, and the E95 bandwidth was less than 0.55pm, when tested with an MO chamber that has undergone 12Bpulses.

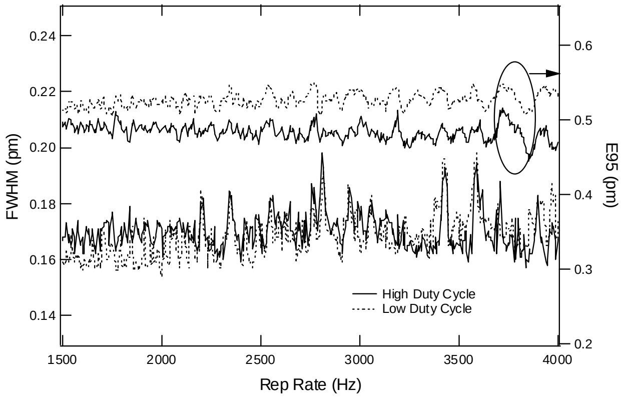

Fig.13: FWHM and E95 bandwidths vs repetition rate with a 12Bpulses old MO chamber, measured from 1500Hz to 4000Hz with 10Hz increments.

CONCLUSION

A large number of XLA-100 production lasers have been shipped to the integrators, and some systems have already been installed at chip fabrication lines. Typical performance data monitored during the manufacturing final test is presented. The results from the XLA-100 reliability test are discussed. The lifetest provides valuable data regarding long-term MOPA system performance and reliability, and it helps to identify the need for further system design improvements. A new long life chamber was designed, and it has demonstrated lifetime exceeding 12Bpulses while providing a stable optical performance.

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