XLR 500i: Recirculating Ring ArF Light Source for Immersion Lithography

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ABSTRACT

As Argon Fluoride (ArF) lithography moves into high volume production, ArF light sources need to meet performance requirements beyond the traditional drivers of power and bandwidth. The first key requirement is a continuous decrease in Cost of Ownership (CoO) where the industry requirement is for reduction in ArF CoO in line with the historical cost reduction demonstrated for Krypton Fluoride (KrF) light sources. A second requirement is improved light source performance stability. As CD control requirements shrink, following the ITRS roadmap, all process parameters which affect CD variation need tighter control. In the case of the light source, these include improved control of bandwidth, pulse energy stability and wavelength. In particular, CD sensitivity to exposure dose has become a serious challenge for device processing and improvements to laser pulse energy stability can contribute to significantly better dose control.

To meet these performance challenges Cymer has designed a new dual chamber laser architecture. The Recirculating Ring design requires 10X less energy from the Master Oscillator (MO). This new configuration enables the MO chamber lifetime to reach that of the power amplifier chamber at around 30Bp. In addition, other optical modules in the system such as the line narrowing module experience lower light intensity, ensuring even longer optics lifetime. Furthermore, the Recirculating Ring configuration operates in much stronger saturation. MO energy instabilities are reduced by a factor of 9X when passed through the Ring. The output energy stability exhibits the characteristics of a fully saturated amplifier and pulse energy stability improvement of 1.5X is realized. This performance enables higher throughput scanner operation with enhanced dose control. The Recirculating Ring technology will be introduced on the XLR 500i, Cymer's fifth-generation dual chamber-based light source built on the production-proven XLA platform. This paper will describe the design details and performance characteristics of the new laser architecture.

Keywords: ArF, Laser, Lithography, Recirculating Ring, CD control, bandwidth, energy stability, Throughput

1. INTRODUCTION

With the advent of immersion lithography, scanners are required to provide improved resolution and critical dimension (CD) control with higher throughput to maintain low operating costs. Higher numerical apertures (NA), polarized illumination and optical proximity corrections (OPC) are some of the key changes and improvements that can contribute to meeting the required on-wafer results for 65nm and below. These improvements require enabling light source technology that can provide low and stable bandwidth, highly polarized light and very stable optical characteristics in general. Furthermore, with more advanced nodes, there is a trend to deploy double-patterning (DP) lithography to resolve smaller features, which drives a need for higher throughput scanners. This in turn requires higher power lasers to enable higher throughput, improved energy stability to maintain good dose control, lower energy density and longer pulse duration to minimize optics damage. Excimer lasers have evolved to meet these challenges through the use of dual chamber designs and, more recently, through the introduction of recirculating ring technology. This paper describes the benefits of ring technology, including improved pulse energy stability for tighter dose control, which is particularly important for higher power applications. Also described here are advances in bandwidth control, which enable higher NA photolithography without increasing CD sensitivity, as well as continuing improvements in the area of lowering operating costs.

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2. POWER REGENERATIVE AMPLIFICATION TECHNOLOGY

The introduction of dual chamber design, known as MOPA (Master Oscillator Power Amplifier) enabled the decoupling of bandwidth and power design requirements, such that one chamber could be optimized to deliver the narrow spectral bandwidth (Master Oscillator, or MO), while the second chamber could be designed for optimal power (Power Amplifier, or PA). Since spectral bandwidth did not need to be compromised for higher energy pulses, this approach allows for both the simultaneous reduction of bandwidth—thereby enabling higher NA—as well as the boosting of power, which provides higher throughput. In addition, with a higher nominal energy per pulse at the wafer, the dual-chamber system can fire fewer pulses per exposure window, thereby reducing the operating cost associated with the number of pulses fired. While this design has successfully served the requirements for early generations of immersion scanners, we realized that traditional laser physics offered an option to further improve the performance of this system with a simple modification. In this modification, we closed the standard tilted double-pass optical path through the amplifier chamber with an output coupling optic, to form a recirculating resonant structure. This is traditionally called a ring resonator or recirculating ring. With this approach, we leverage the proven dual chamber platform to assure a smooth, low-risk transition, to ensure the chipmaker of high reliability.

3. HIGH POWER CHALLENGES

Extending dual chamber lasers to higher power while maintaining good energy stability can be achieved by increasing pulse repetition rates beyond the current 6 kHz regime. This would allow more pulses in a scan window, effectively increasing overall power, while leveraging an ‘averaging’ effect of this higher pulse count to compensate for pulse-to-pulse variance. However, this leads to a laser of increasing size and cost just to accommodate higher power components as well as a higher operating cost since key components have lifetimes proportional to the total number of pulses. The alternative approach developed here mitigates the need for higher repetition rates, and instead enables higher per-pulse energy while improving repeatability.

The key to this new design is to close the optical path within the amplifier to enable regenerative amplification of the seed pulse from the MO chamber. The arrangement is shown in Figure 1.

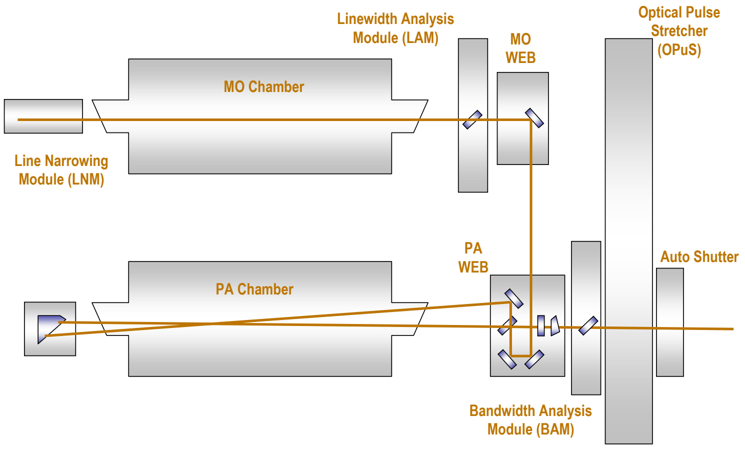

Fig 1. Recirculating Ring concept extends the dual chamber architecture by directing the master oscillator (MO) beam into a power regenerative amplification stage (PRA) chamber, which improves pulse-to-pulse energy repeatability of the system output.

4. IMPROVED DOSE STABILITY

In order to meet the dose stability requirements within a smaller scan window (fewer pulses), significant improvement in energy stability has been attained with the enhanced optical configuration. The XLR 500i power amplifier is aptly called a power ‘regenerative’ amplifier (PRA) due to the fact that each pulse experiences multiple passes and is successively amplified. We denote the system utilizing a PRA amplification stage as a MOPRA (Master Oscillator Power Regenerative Ammplifier). It is important to note that the system operates as a true regenerative amplifier – without an injected seed there is no output from the PRA subsystem.

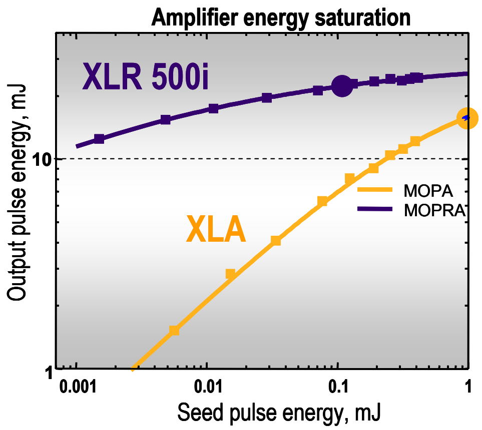

Figure 2 - Saturation curves for system output power as a function of seed (injected MO) power. The PRA configuration curve (XLR in the legend) saturates at lower power and is deeper into gain saturation – there is less variation in output pulse energy with fluctuations in input pulse energy in comparison to a conventional dual-chamber laser (XLA in the legend).

This multi-pass PRA dampens any input pulse instabilities from the MO chamber by running in “hard saturation”, which results in previously unattainable low pulse to pulse energy stability. This evolutionary approach now allows the PRA to be optimized for an even higher state of saturation than other dual chamber designs thereby further reducing discharge instabilities that could adversely affect optical performance. While a conventional, dual chamber laser amplifies the MO pulse (seed) proportionally to its energy, the recirculating ring arrangement is less sensitive to the MO pulse variations (Figure 2). This effectively leads to a 1.5X increase in intrinsic pulse-to-pulse energy stability (Figure 3) and the same 1.5X improvement in dose stability that enables superior yield due to improved CD control.

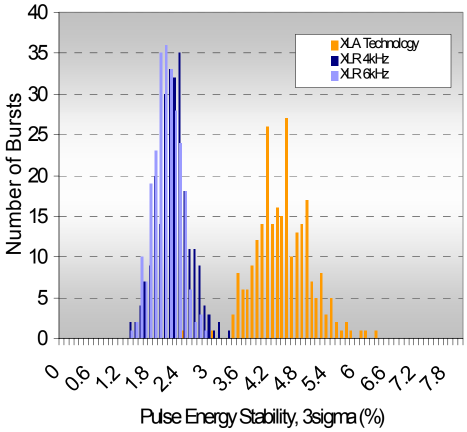

Figure 3 - Energy stability comparison between a dual-chamber laser (XLA) vs. a recirculating ring technology laser (XLR), illustrating a 1.5x improvement

Figure 4 illustrates how the improved energy stability of a recirculating ring leads to improvements in dose stability. This is particularly important for higher power applications as envisioned in double patterning (DP) lithography, where higher energies combined with smaller windows necessitate much tighter energy stability.

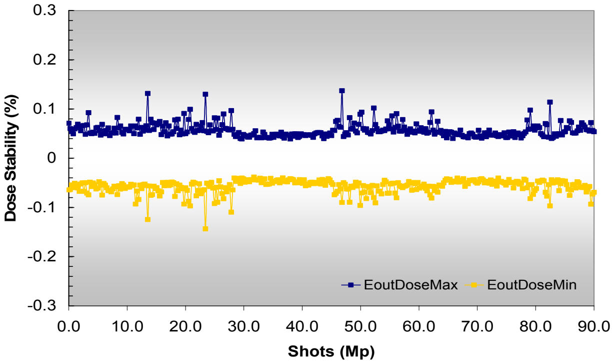

Figure 4 – Improved energy stability leads to better dose control, shown here through a test that exercises the operating conditions of the laser.

5. BANDWIDTH IMPROVEMENTS

Spectral bandwidth also plays a key role in the resultant features printed on a wafer, and its stability can enable better lithography optics that need not compromise resolution to address chromatic aberrations, for instance. With the recirculating ring architecture stability is also improved by tight timing synchronization control, tight voltage control, repeatable pulse power transfer and stable discharge conditions. Timing synchronization between the MO and the PRA chambers is dynamically adjusted to achieve maximum efficiency, which leads to better performance stability. Since the recirculating ring laser has lower sensitivity to timing variations, it inherently produces a more stable output (Fig. 5). This translates to better energy stability across a wide operating window of repetition rates (Fig. 6).

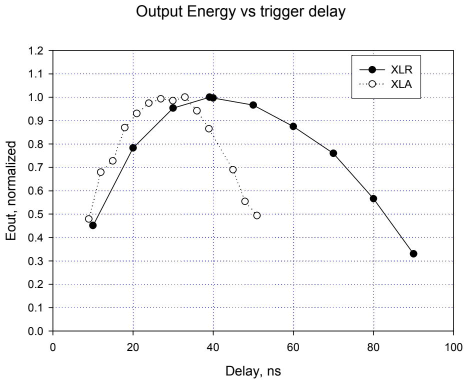

Figure 5 – Output energy vs. timing between MO and PA chambers. The recirculating ring laser (XLR) has lower sensitivity to timing variations compared to a conventional dual chamber laser (XLA).

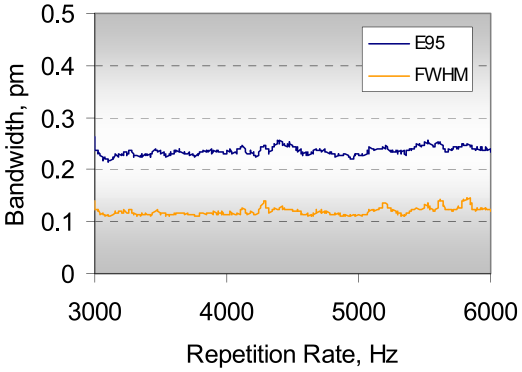

Figure 6 – Bandwidth stability as a function of repetition rate showing consistent performance over a large operating regime, measured as full-width at half maximum (FWHM) and at the 95% percentile (E95) of the distribution.

6. ACTIVE BANDWIDTH STABILIZATION

Further improvements in bandwidth control have been demonstrated using optical techniques for bandwidth modulation. In a typical excimer laser, narrow bandwidths are attained with a grating-based line narrowing module (LNM). The grating acts as a wavelength narrow-pass filter, effectively limiting the spectral characteristics to a narrow regime. The ability to add modulation within this device can provide active bandwidth stabilization (ABS), which is a control technique that actively compensates for bandwidth variations over the life of the laser consumables, thereby improving stability of the light source. In the XLR 500i laser, the ABS feature enables closed-loop active bandwidth stabilization, and results in significantly improved stability compared to non-stabilized configurations (Fig. 7).

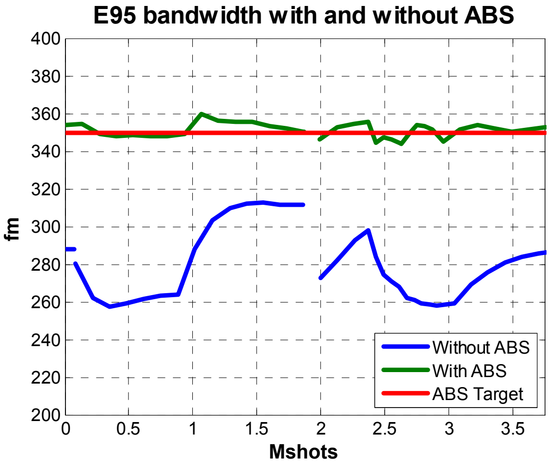

Figure 7 - E95 bandwidth stability during various duty cycles and repetition rate changes for a typical laser (blue curve) and one with ABS enabled (green curve).

This same method can be used to match multiple photolithography systems to the same spectral purity, enabling flexibility to the manufacturing process, or achieving cross-platform matching, where different generation lithography systems can be more closely matched in optical performance. This application is named ‘tunable’ active bandwidth stabilization (Tunable ABS), since it allows the user to change the bandwidth within the same lithography system for matching purposes (Fig. 8).

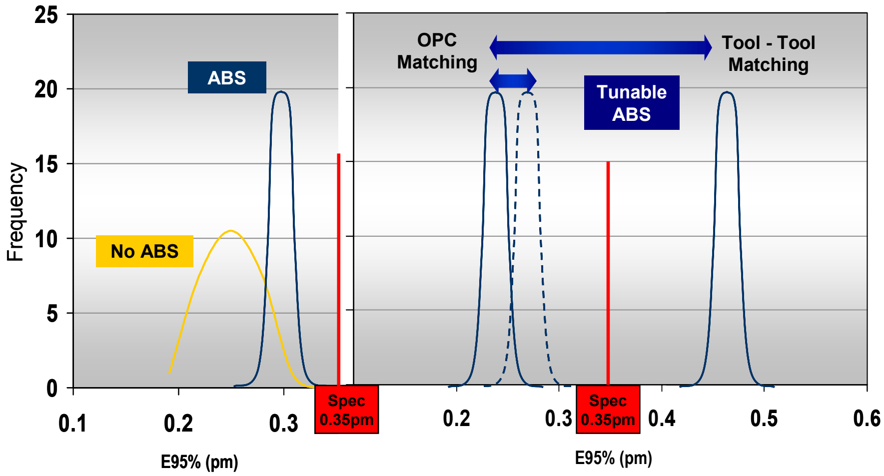

Figure 8 - Active Bandwidth Stabilization (ABS) leads to higher spectral purity (left), while Tunable ABS (right) allows for user dynamic control of bandwidth for tool-tool or OPC matching.

7. ENERGY DENSITY AND PULSE DURATION

One of the key concerns of a higher power laser is its potentially damaging effects on delicate UV optics. Another by-product of the multi-pass architecture again provides an advantage in a more uniform beam that results in peak energy densities on par with lower power lasers that do not have the ring technology (Fig. 9).

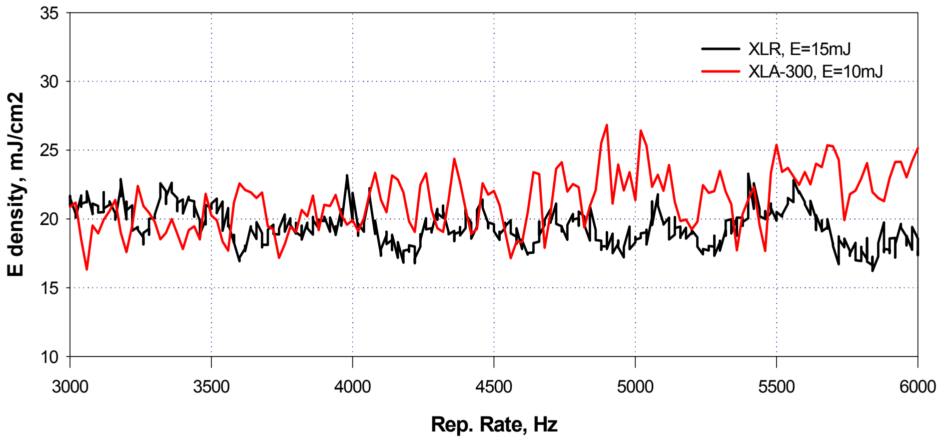

Figure 9 - Energy density across a resonance scan for a dual chamber configuration (XLA) running at 10mJ and a ring technology laser (XLR) operating at 15mJ.

The same architecture also results in an intrinsically longer pulse duration, again due to the multiple passes, that further protects optics from damage by limiting the effects of compaction that high peak energies can create. By using the same pulse-stretching techniques as the XLA lasers, the XLR can deliver even longer pulses, further mitigating the risk of optic damage (Fig. 10).

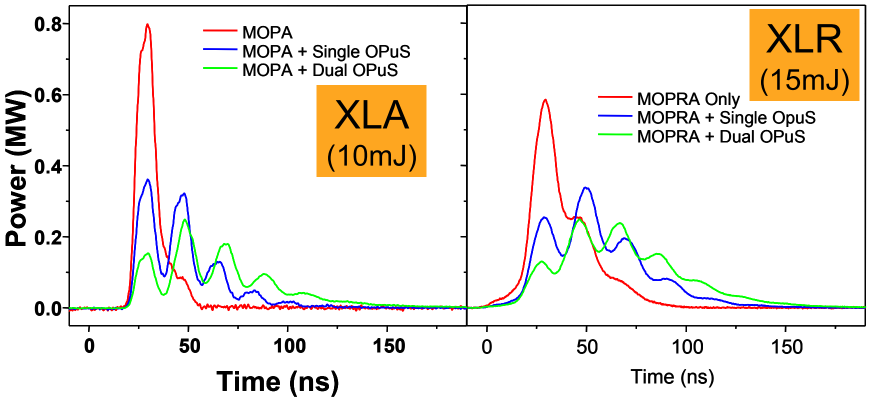

Figure 10 - Pulse duration without pulse stretching as well as 2x and 4x pulse stretching optics, showing the intrinsically longer pulse widths with the XLR.

8. COST OF OWNERSHIP REDUCTION

Even as technology improvements are developed, continuous vigilance in operating costs is necessary to remain competitive in the industry. Opportunities for reducing cost of ownership (CoO) metrics have been further explored, with the most recent advances in the area of higher availability. One of the detractors in laser availability (and hence scanner availability) is the periodic refreshing, or refilling, of the gas discharge chambers in order to maintain optimum gas mixtures as the constituents of the mixture, such as fluorine, are depleted. This refill event can take up as much as 20 min, which would not be long were it not for its high frequency: typically every 100M pulses or 1 – 3 days (depending on utilization). With 6 kHz lasers, this can represent as much as 2% of productive time lost doing refills (Fig. 11). Using a unique method of controlling the active gas mixture in the discharge chambers, a technique called gas lifetime extension (GLX) has been developed that reduces the need for chamber refills by at least a factor of 10, or every 1 billion pulse

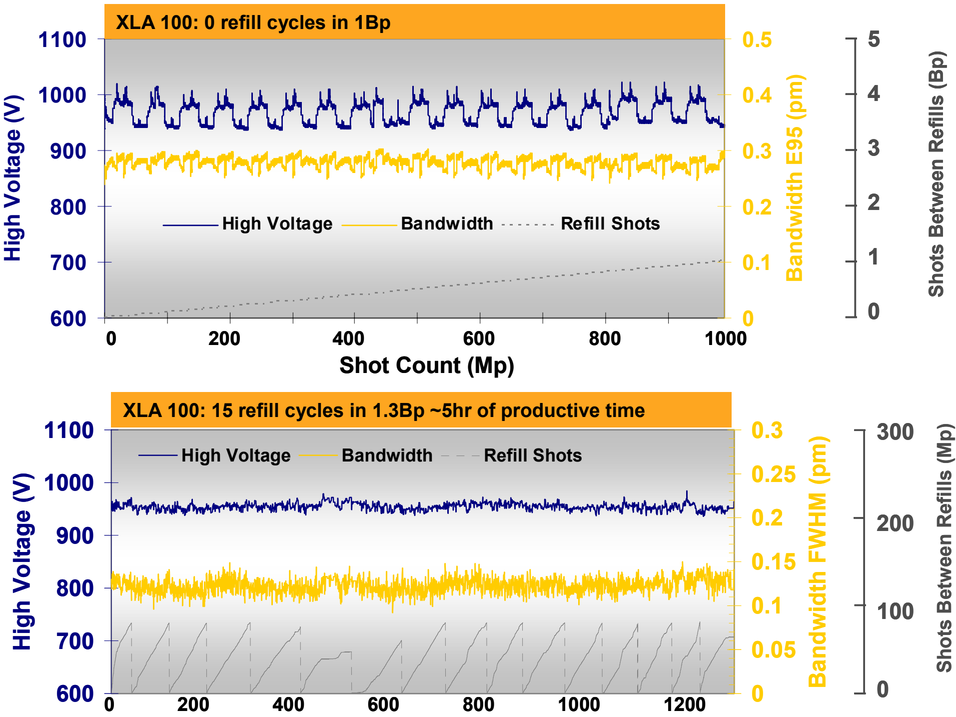

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Figure 11 - Typical gas refill sequence during normal operation: 15 cycles in 1.3B pulses representing about 5 hours of lost productive time (top). Gas lifetime extension (GLX) technology eliminates the need for refills by a factor of 10 while preserving stable laser performance (bottom). In the bottom example here, the laser is further exercised through multiple sequences of high and low duty cycles which results in voltage variations, although it does not significantly affect bandwidth performance.

9. SUMMARY

With more stringent requirements placed on lasers as light sources for photolithography tools, a new generation of laser technologies is emerging that addresses throughput improvements with higher power, while achieving resolution improvements through tight control of energy stability and spectral performance. Extending a proven, dual-chamber architecture by introducing a ring cavity simplifies the transition to next-generation technology nodes without compromising operating costs or complexity. In addition, novel improvements in bandwidth stabilization and control (ABS and tunable ABS) enable higher yields and greater manufacturing flexibility to the semiconductor manufacturer. Finally, continual reductions in operating costs via increased availability are being demonstrated via discharge gas lifetime extension (GLX). The result of these developments has been embodied in a laser family under the Cymer trade name of XLR 500i, which will coincide with the implementation of immersion lithography systems for 45nm device technologies and beyond.