Active Spectral Control of DUV light sources for OPE minimization

Wayne J. Dunstan[1], Robert Jacques, Robert J. Rafac, Rajasekhar Rao, Fedor Trintchouk,
Cymer Inc., 17075 Thornmint Court, San Diego, CA, 92127, USA

ABSTRACT

The variation of CD with pitch, or Optical Proximity Effect (OPE), in an imaging system shows a behavior that is characteristic of the imaging and process conditions and is sensitive to variations in those conditions. Maintaining stable process conditions can improve the effectiveness of mask Optical Proximity Correction (OPC). One of the factors which affects the OPE is the spectral bandwidth of the light source. To date, passive bandwidth stabilization techniques have been effective in meeting OPE control requirements. However, future tighter OPE specifications will require advanced bandwidth control techniques. This paper describes developments in active stabilization of bandwidth in Cymer XLA and 7010 lasers. State of the art on board metrology, used to accurately measure E95 bandwidth, has enabled a new array of active control solutions to be deployed. Advanced spectral engineering techniques, including sophisticated control algorithms, are used to stabilize and regulate the bandwidth of the light source while maintaining other key performance specifications.

Keywords: laser, bandwidth, FWHM, E95, active, control

1. INTRODUCTION

The variation of CD with pitch, or Optical Proximity Effect (OPE), in an imaging system shows a behavior that is characteristic of the imaging and process conditions and is sensitive to variations in those conditions. Maintaining stable process conditions is considered important to maintaining the effectiveness of mask Optical Proximity Correction (OPC).

The recent work of Huggins et. al[1] describes how controlling the spectral properties of the laser light, specifically E_{95} bandwidth, has an effect of similar magnitude to those from other control parameters, such as focus shift, dose shift and partial coherence shift. The bandwidth metric, E_{95}, is defined as the width of the spectrum (typically in picometers) that contains 95% of the integrated spectral intensity. A second bandwidth metric that is commonly employed is the Full Width at Half-Maximum (FWHM), which although easier to measure than E_{95}, does not affect OPE as significantly.

Stabilizing E_{95} bandwidth has been a focus of DUV laser design for some time now, and considerable effort has been invested in *passive* improvements to bandwidth stability. By passive, we mean not employing *active* control methods such as sensing a measured signal and performing feedback or feedforward actuation. Some of the passive improvements to DUV laser technology have involved baseline system modifications that dampen acoustic disturbances in the discharge region and those that reduce the system sensitivity to optical power loading.

To date, passive bandwidth stabilization techniques have been effective in meeting OPE control requirements. However, future tighter OPE specifications will require active control techniques to not only improve the stability of E_{95} bandwidth, but also regulate E_{95} bandwidth to a desired setpoint. Figure 1 relates the concepts of stability and setpoint regulation to those of passive and active control. The left most plot (Nominal) depicts the E_{95} variability versus time as a system baseline. The middle plot (Passive) illustrates that with passive improvements we aim to improve E_{95} *stability*, reduce the E_{95} *variability*, and usually lower the E_{95} *setpoint*. The right most plot (Active) illustrates that with active control methods we can further refine the E_{95} stability and variability. We also introduce the ability to *regulate* the E_{95} to a desired setpoint on the fly. This E_{95} setpoint may be chosen so as to minimize OPE or to provide tool-to-tool matching.

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[1] wdunstan@cymer.com phone: int+1-858-385 6177, www.cymer.com

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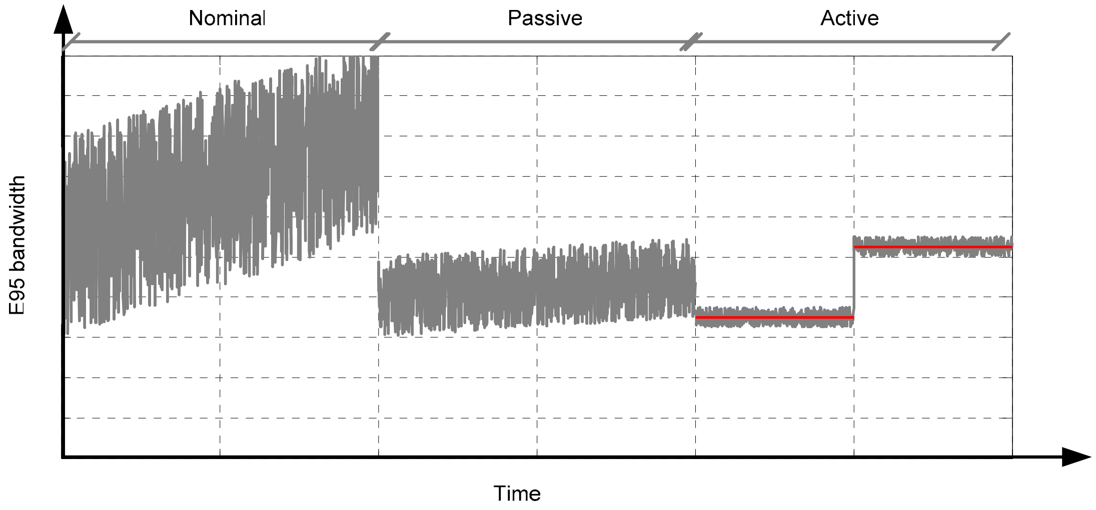

Figure 1: E_{95} stability and setpoint regulation for passive and active control methodologies.

State of the art on board metrology, used to accurately measure E_{95} bandwidth, has enabled a new array of active control solutions to be developed to stabilize and regulate the bandwidth of the light source while maintaining other key performance specifications.

This paper describes some of the developments in active stabilization of bandwidth that could be utilized on Cymer XLA and ELS laser platforms.

2. ACTIVE SPECTRAL CONTROL

The performance of Active Spectral Control (ASC) methods depend heavily on the statistical accuracy of the measured E_{95} (sensing) and also on the *method* of effecting change to E_{95} (actuation).

Figure 2 shows the system block diagram for the ASC-equipped laser platform.

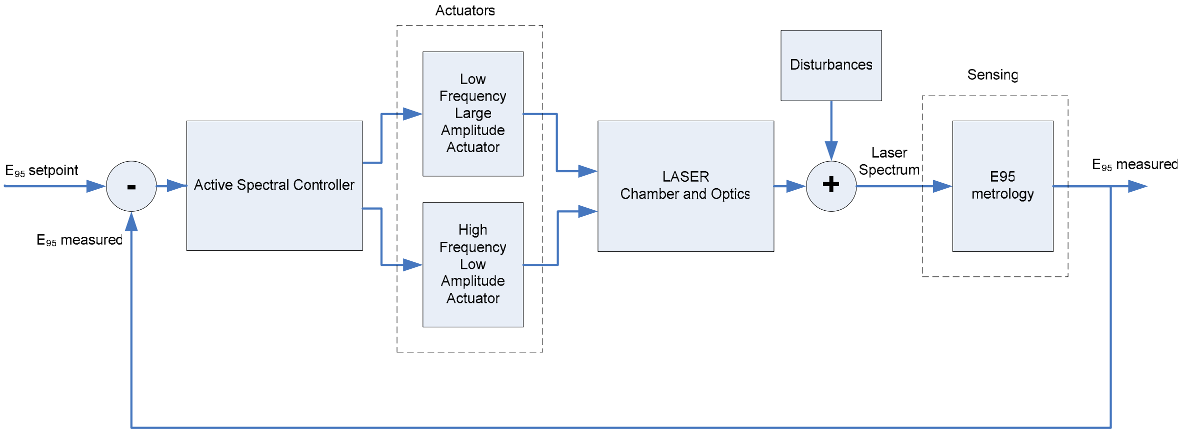

Figure 2: Block diagram of Active Spectral Control system.

Referring to Figure 2, the laser chamber and optics (depicted in the center block) are subjected to disturbances and produce a light spectrum that is the input to the E_{95} metrology. The output of this sensor is the measured E_{95} bandwidth.

Recent advances in onboard etalon spectrometer technology have enabled calculation of E_{95} bandwidth with a precision comparable to that of a state-of-the-art high-resolution Echelle grating spectrometer[2].

Along with being a displayed laser diagnostic value which can be used for external process monitoring, this measurement is fed back to the ASC controller after being compared to a desired E_{95} bandwidth setpoint. The ASC controller uses this information, in combination with information from other laser signals, to calculate input signals to both actuators. The actuators then induce a corrective action to the laser behavior in order to move the measured E_{95} towards the E_{95} setpoint. This closes the feedback loop.

The DUV laser is a Multiple-Input Multiple Output (MIMO), time varying, nonlinear system and the choice of actuator methods must be chosen carefully as it will almost certainly cause other effects to the laser performance. These effects could be desirable or they could be in opposition to certain laser performance specifications.

The focus of this work is to investigate dual stage actuator designs, primarily because of their superior ability to ameliorate the wide array of disturbances that may be imposed on the laser. Figure 2 illustrates the dual stage actuators being driven by different control signals, and affecting the laser behavior through separate inputs. These actuators are designed to work in tandem, but are also each optimized for a particular class of disturbance. Together they hold the E_{95} bandwidth at a desired setpoint, even though the laser may be being subjected to a wide array disturbances.

Some laser disturbances have been minimized by improving other onboard control systems; for example, minimizing chamber thermal and pressure variations. However other disturbances, such as changes in laser output energy and duty cycle, are characteristic of how the laser is operated. Aging of components and alignment changes can also affect E_{95} bandwidth.

Disturbances may be categorized by the time scale and magnitude by which they affect E_{95} bandwidth, as illustrated in Figure 3. Setpoint changes in laser energy are low magnitude disturbances that affect E_{95} on a very fast timescale, typically msec to sec. Changes in duty cycle and gas aging, affect E_{95} bandwidth in the seconds to hours timescale with larger magnitude. Effects of optical component aging are experienced in the days to weeks timescale, and are the largest magnitude disturbances.

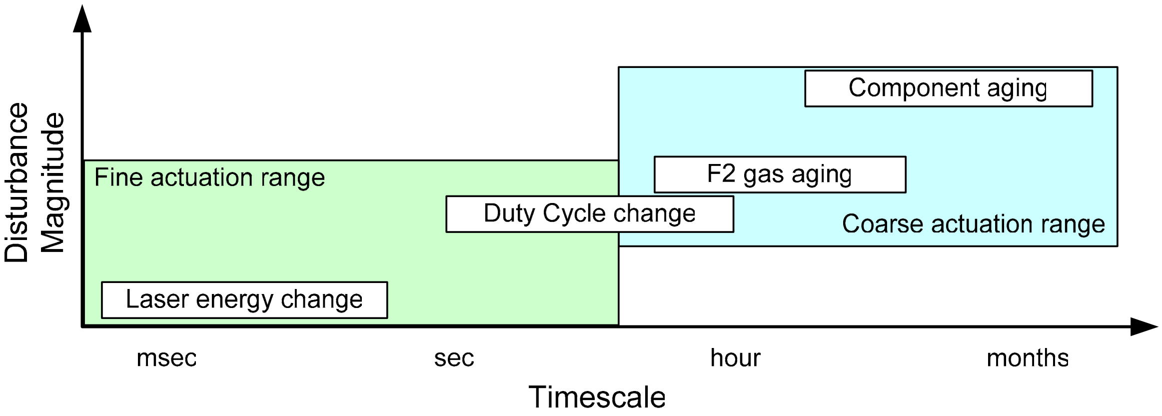

Figure 3: Disturbance categories to ASC.

Within the dual stage actuator framework, control action may be divided into *coarse* actuation and *fine* actuation. Coarse actuators target large magnitude changes that occur at low frequency. In Cymer lasers this may include large E_{95} setpoint changes, gas aging effects and the long timescale component of duty cycle changes. Fine actuators target the smaller magnitude but higher frequency disturbances, such as laser energy, and even the fast component of duty cycle changes. The coarse actuators also serve to de-saturate, or re-center, the fine actuator within its control range. That is, as the fine actuator's control output trends towards its minimum or maximum value, then the coarse actuator applies corrective action in such a way as to restore the fine actuator back towards its centered value, nominally 50% if the control authority is balanced in both the positive and negative directions.

One viable choice for the coarse actuator is F_2 gas injection, which adjusts the F_2 concentration of the laser chamber. For dual chamber systems, one of the fine actuator choices available is control of the relative time delay, denoted Δt_{MOPA}, between the commutation of the Master-Ocilllator (MO) and Power-Ampifier (PA) pulsed-power. For single chamber systems the alternatives include manipulation of the curvature of the Linewidth Narrowing Module (LNM) grating surface. In the following sections we explore each of these methods in more detail.

2.1. Fluorine Concentration

Regulating the Fluorine (F_2) gas concentration in the laser chamber provides an effective means of coarse control of E_{95} bandwidth. The chamber is the gain medium between the fully reflective Line Narrowing Module (LNM) and the partially reflective Output Coupler (OC). The LNM progressively narrows the spectrum of incident light after each round trip to the OC and back. Each round trip through the chamber increases the stimulated emission of light and therefore the light output energy. Eventually the stimulated emission depletes all of the energy stored in the gain medium and the laser pulse ends.

Increasing the chamber F2 concentration increases the gain, speeding the build-up of energy in the cavity. The stored energy is depleted more rapidly because there is more stimulated emission, so the laser is above the oscillation threshold for less time. Due to the finite speed of light, this equates to fewer round trips, which decreases the line narrowing of the light, and thus the E_{95} bandwidth is larger. Decreasing the chamber F2 concentration has the opposite effect, it reduces the E_{95} bandwidth.

However, the effect of changing the F_2 concentration is a multifaceted problem. It also affects other laser performance parameters, including voltage and energy stability. As such, the regulation of F_2 concentration is a multiple input optimal control problem. Figure 4 shows how E_{95} bandwidth of light exiting the laser varies as F_2 concentration is adjusted in the MO chamber on a typical MOPA configuration. The MO chamber response in the Cymer XLA platform (MOPA system) is similar to the single chamber response of a Cymer ELS-7010 platform.

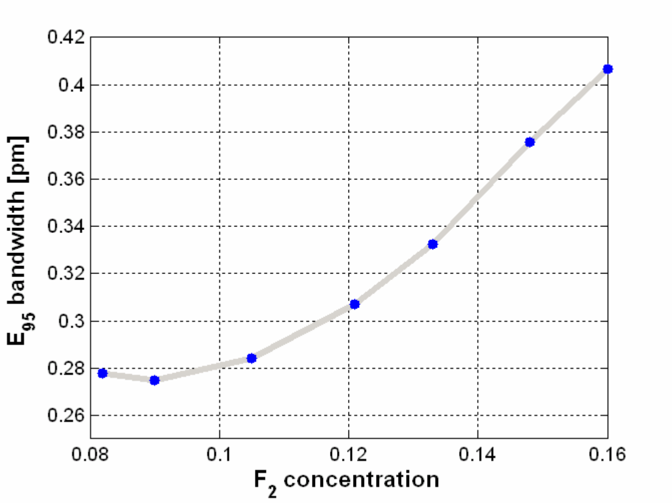

Figure 4: E_{95} bandwidth control authority using F_2 concentration

The principle advantages of using F_2 concentration as a coarse actuator to control E_{95} bandwidth are:

1. The addition of F_2 to the laser gas, or its natural depletion as the laser is operated, affects other chamber performance parameters slowly enough (minutes) that other fast controllers (energy, wavelength, timing) are effectively decoupled and are able to track without error.

2. The available range of actuation is large enough to ameliorate the sources of bandwidth deviation being targeted, namely long term duty cycle variations, gas aging and component aging.

Figure 5 shows the effect of the F2 injection coarse-actuator on E_{95} bandwidth on a single chamber Cymer ELS-7010 platform. The data shows E_{95} bandwidth measurements taken every 30 seconds over a 10 hour test. The laser was fired at 75% duty cycle and the output energy was 10mJ. The controller was able to regulate E_{95} to a 0.84 pm setpoint with and a Total Included Range (TIR) of less than 50 fm for more than 450Mshots.

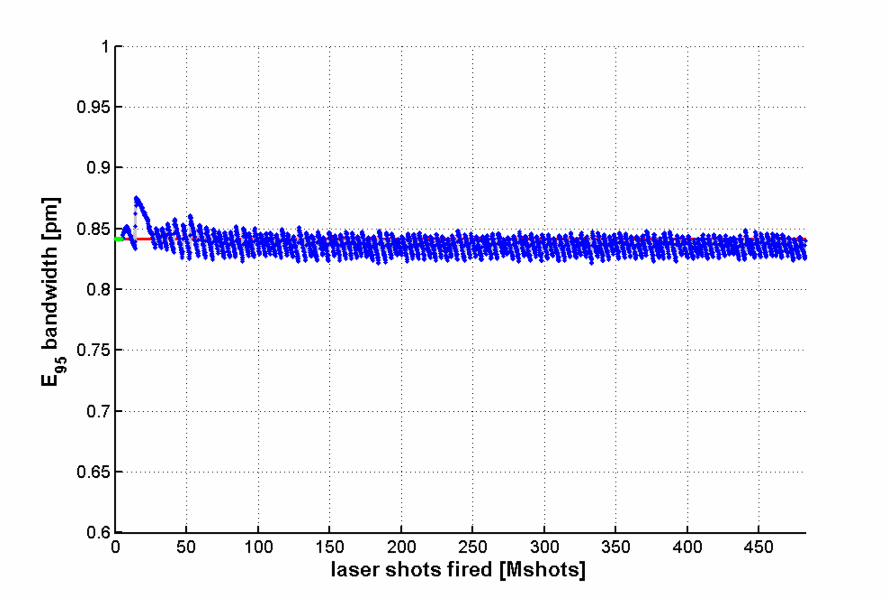

Figure 5: E_{95} bandwidth control using F_2 gas on a Cymer 7010 laser.

Figure 6 shows the effect of the F_2 injection coarse-actuator on E_{95} bandwidth on a dual-chamber Cymer XLA 200 platform[3]. The data shows E_{95} bandwidth measurements taken every 30 seconds over a 10 hour test. The laser was fired at 75% duty cycle and the output energy was 10mJ. The controller was able to regulate E_{95} to a 0.275 pm setpoint with and a Total Included Range (TIR) of less than 15 fm. Both of these experiments illustrate the extremely tight control achievable with F_2 injections.

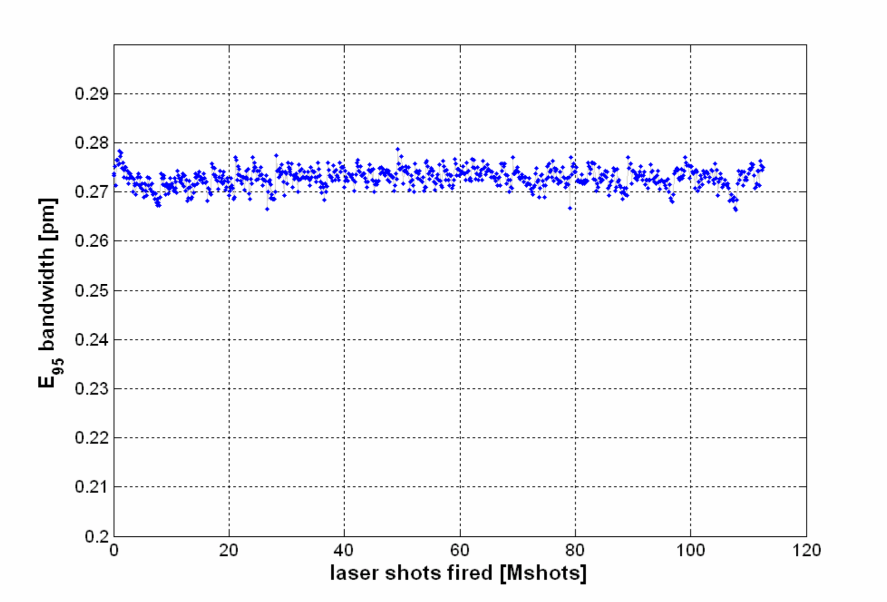

Figure 6: E_{95} bandwidth control using F_2 injects only on a Cymer XLA series.

2.2. Differential Commutation Time

In dual chamber lasers in a MOPA configuration, E95 bandwidth is sensitive to the relative time delay, denoted ΔtMOPA , between the commutation of the MO and PA pulse power. The MO pulse becomes more line-narrowed over its duration as explained in section 2.1. The effect of this is that as the PA chamber is fired later relative to the MO chamber, it selects a more line narrowed portion of the MO pulse and the effective E95 bandwidth of the laser decreases. Figure 7 shows how E95 bandwidth varies as differential firing time is adjusted on a typical MOPA configuration.

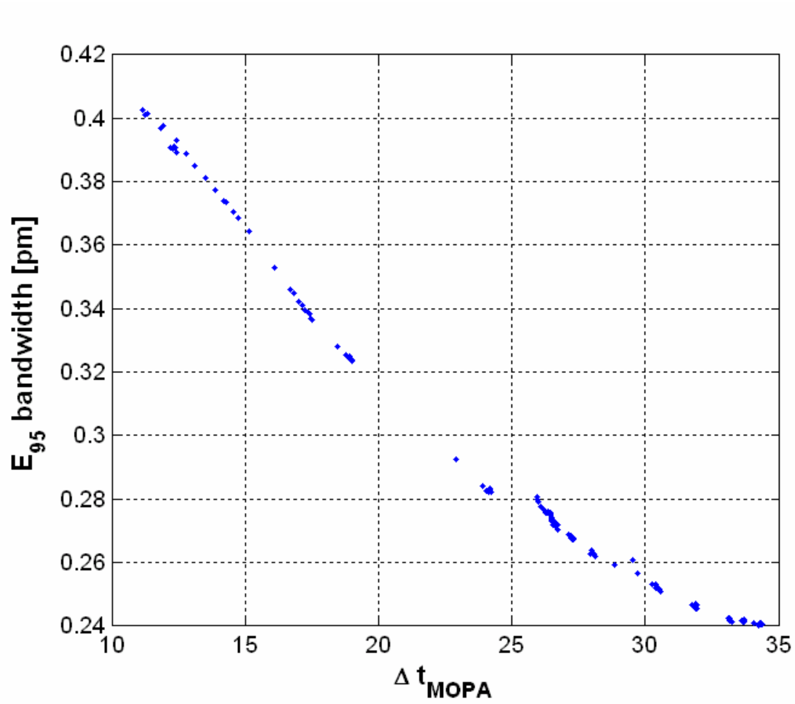

Figure 7: E_{95} bandwidth control authority using Δt_{MOPA} .

The principle advantages of using differential firing time as a fine actuator to control E_{95} bandwidth are:

1. The measurement of E_{95} and the change of Δt_{MOPA} both occur on a tens-of-pulses time scale allowing for very high frequency disturbance rejection. That is, disturbances can be suppressed very quickly.

2. The available range of actuation is large enough to ameliorate the sources of bandwidth deviation being targeted, namely laser energy and duty cycle variations.

Figure 8 shows the effect of the Δt_{MOPA} fine-actuator and F2 inject coarse-actuator, dual stage controller in action. The data shows maximum and minimum E_{95} bandwidth measurements taken every 30 seconds during a seven hour test. The laser was fired at 75% duty cycle and the output energy (nominally 10mJ) was switched between 9 mJ and 11 mJ every half hour. The lower set of curves show the behavior when only the coarse actuator (F2 inject control) is applied and the upper curves show the effect when the fine actuator (Differential commutation control) is used to stabilize E_{95} bandwidth and shift it up to a setpoint value of 0.35 pm. The improvement is dramatic. Timing control has stabilized E_{95} bandwidth to well within the limits of the E_{95} metrology.

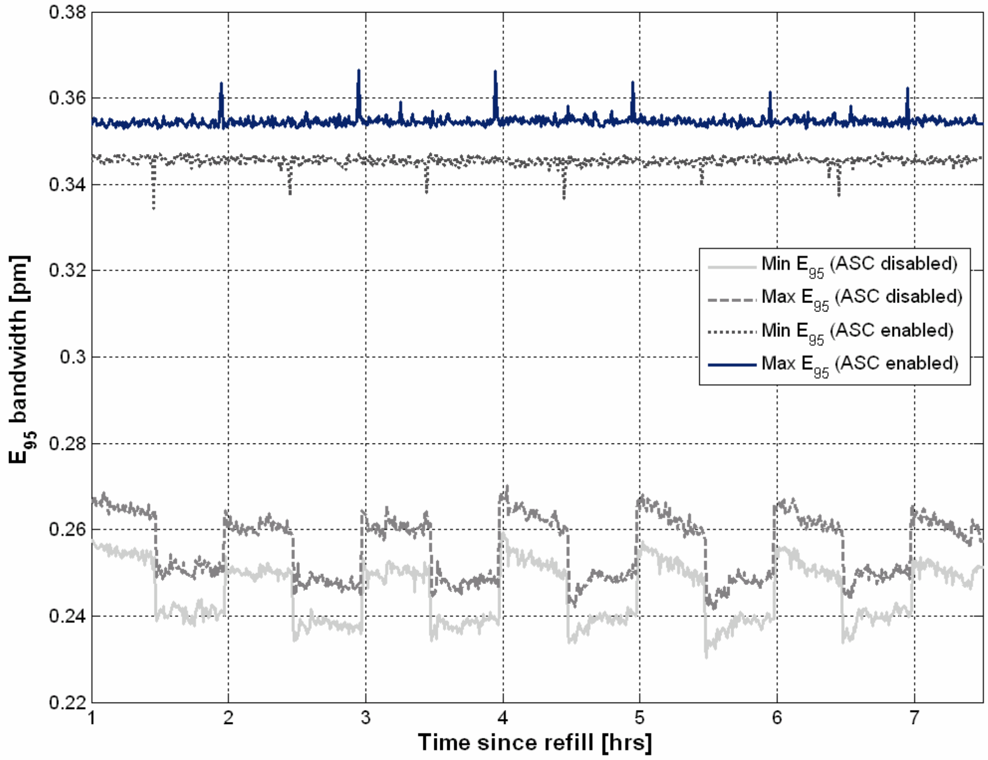

Figure 8:E_{95} bandwidth control comparison using (a) coarse actuator only, lower plot (b) coarse and fine actuators, upper plot.

2.3. Line Narrowing Grating Curvature

Altering the optical wavefront within the laser's line narrowing element by changing the grating surface is an effective optical method of regulating E_{95} bandwidth with fine resolution on a relatively fast time scale. Figure 9 shows the quadratic relationship between E_{95} bandwidth and the normalized grating curvature.

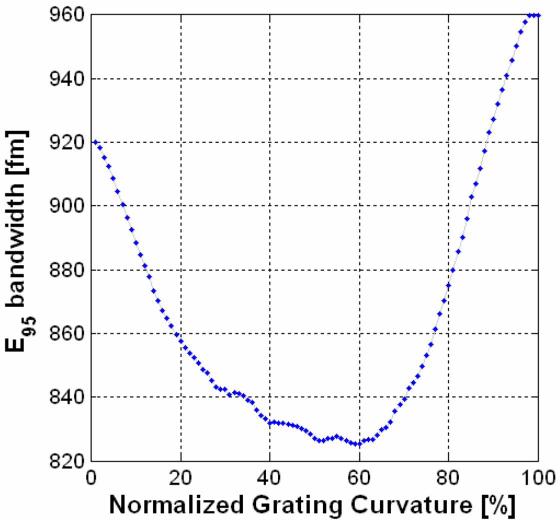

Figure 9: E95 control authority using grating curvature actuator.

The principle advantages of using grating curvature as a fine actuator to control E_{95} bandwidth are:

1. The grating curvature can be changed quickly, thereby allowing fast optical wavefront curvature correction to reduce disturbances and facilitate changes in E_{95} bandwidth setpoint.

2. The available range of actuation is large enough to ameliorate the sources of bandwidth deviation we are targeting, namely duty cycle variations.

Figure 10 shows E_{95} setpoint regulation on a Cymer ELS-7010 platform. The data show the transition between two E_{95} bandwidth setpoints.

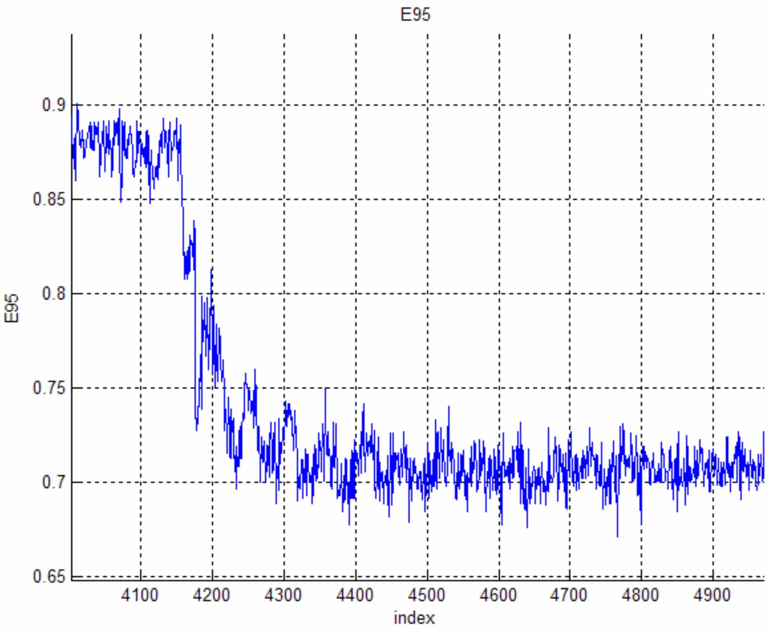

Figure 10: E_{95} setpoint change using grating wavefront curvature change.

3. CONCLUSIONS

As OPE requirements tighten in the future it is expected that E_{95} bandwidth control techniques will be required, necessitating more active control methods to supplement the current passive schemes. As a result, Cymer has developed an array of coarse and fine actuators and dual stage control techniques to meet this need. Complementing these control methodologies with the latest in E_{95} bandwidth metrology has allowed high performance E_{95} stabilization and regulation even while under the influence of various operating disturbances.

Examples of feasible dual stage actuator designs include pairing of an F2 injection controller as the coarse actuator, and either Δt_{MOPA} controller or line narrowing module grating curvature controller, as the fine actuator. Cymer has demonstrated that these methods may be suitable for integration into their light source product range to create tight E_{95} stability bounds and wide E_{95} setpoint regulation required by industry.

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