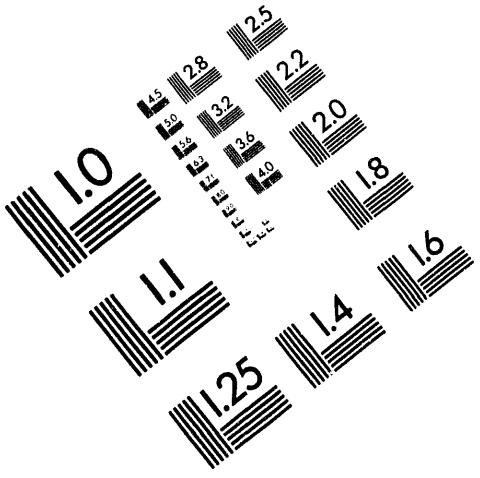

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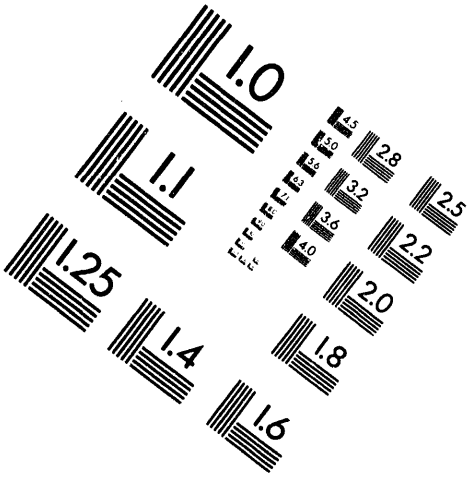

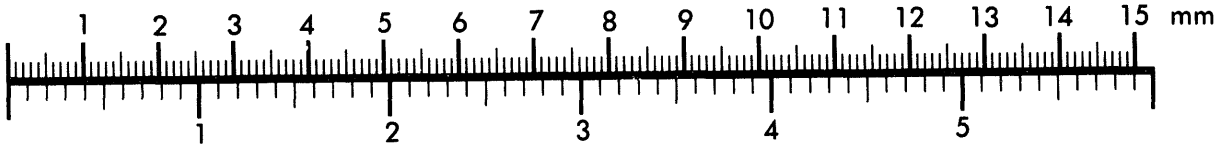

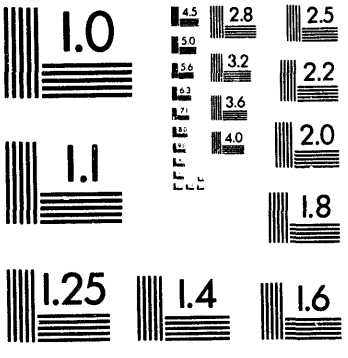

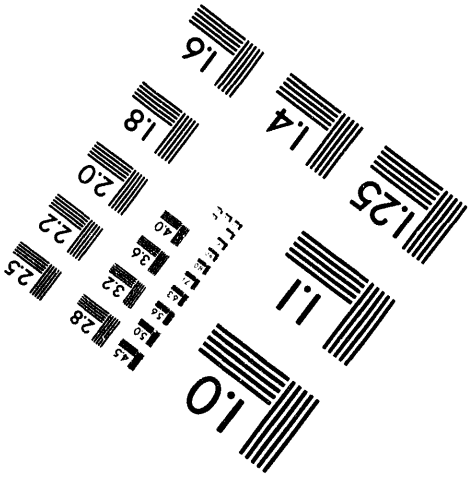

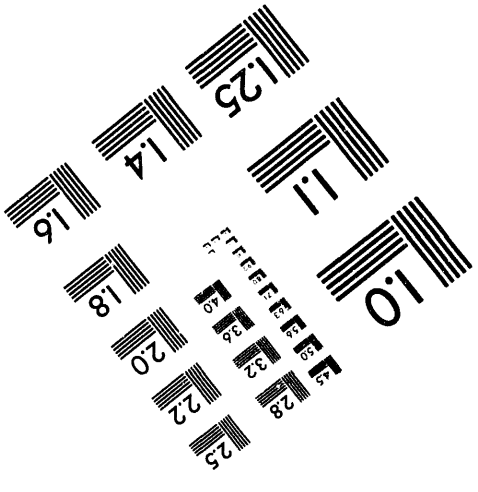

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Solid State Laser Driver for Extreme Ultraviolet Lithography*

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Abstract

We describe the design and initial performance of a Nd:YAG laser master oscillator/phase conjugated power amplifier as a driver for extreme ultraviolet lithography. The design provides 0.5 to 1 joule per pulse with about 5 ns pulse width and excellent beam quality up through 1.5 kHz repetition frequency.

* This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

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Introduction

In support of the national program in Extreme Ultraviolet (EUV) Lithography, we are developing a kilowatt class, laser diode pumped solid state laser drive source. The laser system will produce (1) a peak power in the range of 50 to 200 MW, (2) pulse energy of 0.5 to 1 joule, (3) repetition rate up to 1.5 kHz, and (4) a near diffraction limited beam quality. Pulse duration will be selected in the range of 1 to 10 ns. Pulses shorter than about 3 ns may be limited by non-linear self-focusing (B-integral) within the Nd:YAG. In this eventuality, we will use a stimulated Brillouin scattering pulse compressor to achieve the shortened pulse width.[1]

All the above performance parameters could not be achieved simultaneously by any existing laser. To meet the EUV challenge, including the need for highly reliable operation, we designed a system employing advanced technologies including high power laser diode pump arrays, a zigzag slab high gain amplifier, master oscillator/power amplifier architecture and phase conjugation.

Laser Design

The laser architecture consists of an oscillator and a four pass power amplifier. Figure 1 shows the basic layout. The oscillator produces a single frequency output pulse of about 2 mJ which is formatted to full spatial size (6 mm x 20 mm) for injection into the amplifier. The amplifier is a zigzag slab of Nd:YAG with dimensions of 6 mm x 25 mm x 200 mm. It is pumped by a large array of microchannel cooled laser diodes[2] and cooled by water flow across the 25 mm x 200 mm faces. After the second amplifier pass the beam is directed through a 1/4 wave phase plate and into a phase conjugation cell. Within the cell, stimulated Brillouin scattering (SBS) reflects a beam with reversed phase error. The threshold nature of the SBS process also provides gain isolation between the amplifier stages. Passive polarization rotation, resulting from the double pass through the phase plate, is employed to switch the beam into and out of the four-pass ring. A version of this concept in a glass laser system is successfully operating in our laboratory at a much higher peak power (to 3 GW) and an average power of 150 watts.[3]

The high average power and high repetition rate required for this laser are achieved by using a laser diode pump with a thermally efficient method of packaging in which

diode bars are mounted on microchannel coolers.[2] These coolers minimize the limiting impedance typically associated with heat transport across the cooling water boundary layers of high performance heat sink systems. This modular diode packaging concept allows the construction of large diode arrays with high-duty factor operation. Our system uses two diode array stacks each containing 150 packages. The diode stacks have been tested at 14 kW peak optical power and 2.3 kW average optical output power and are in service as the amplifier pump.

The oscillator is designed to produce 2 to 5 mJ per pulse. This allows sufficient energy for beam shaping and subsequent input to the amplifier. The oscillator is configured to produce a single-frequency output to optimize performance of the SBS phase conjugator. Twenty single-diode-bar modules are stacked and their output spatially formatted using LLNL developed microlenses to end pump a Nd:YAG rod. The diode output is fed to the curved end of a quartz condenser that brings the output to the end of the rod. The laser cavity consists of a two-mirror resonator with a polarizer and a Pockels cell to hold off oscillation during the gain buildup. The single-frequency output is achieved by a technique of self-seeding the cavity in which the Pockels cell voltage is adjusted to retard a bit less than a quarter-wave, causing the Q-switch to leak slightly. As the diodes are pulsed and the cavity gain builds, the oscillator first comes above threshold in a single frequency. This output is sensed and the Pockels cell commanded to fully open. In this way the single frequency builds preferentially, depleting the gain and preventing the emergence of other longitudinal modes. The concept works well and has become the baseline for our system.

Our amplifier employs a slab geometry in order to provide the required per pulse energy and high average power. With the gain isolation provided by the SBS phase conjugator, the need for a high performance Pockels cell is eliminated. Passive polarization rotation, high single pass gain (G=19), and angularly multiplexed slab input are all used to efficiently extract stored energy from the slab. To reach this gain the amplifier geometry was carefully designed to minimize losses caused by amplified spontaneous emission (ASE) and to prevent parasitic oscillation. The slab was constructed from Nd:YAG with nominal dimensions of 25 mm x 6 mm x 200 mm with a 40° wedge angle at the ends. Using our code analysis as a guide, the wedge angle is chosen to minimize ASE losses and eliminate parasitic oscillations.

The 0.5 mJ oscillator output is amplified to 450 mJ in 4 passes of the amplifier. In this entire multipass propagation, the beam is image relayed from the single-frequency oscillator, to the input/output polarizer, to the slab, to the conjugator and then in the reverse sequence back to the input/output polarizer. This relay process is important to ensure that the conjugator obtains the full spatial spectrum of input information necessary for high fidelity of the conjugated return. The high fidelity return allows cancellation of phase errors and the generation of a near diffraction limited output beam.

Laser Performance

The laser system has been built and is being activated. In the first phase of operation we have extracted 0.45 joules per pulse at 200 Hz repetition rate with near diffraction limited beam quality. The laser is presently being installed in the EUV Lithography laboratory at LLNL for an initial phase of integrated testing. Following this activity we will increase the diode drive current and repetition rate and bring the laser up to full power operation.

Acknowledgments

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

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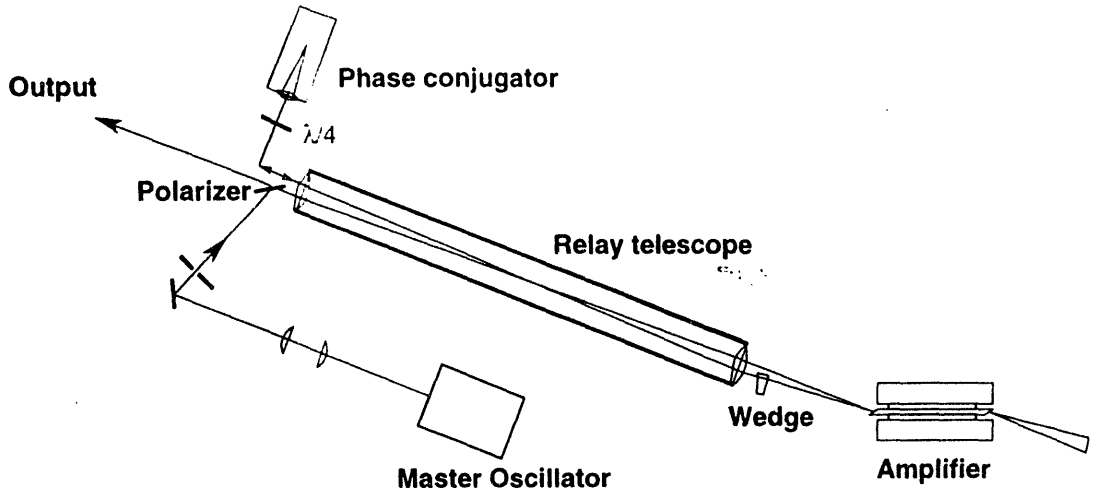

Figure 1. Optical layout of the EUV solid state laser showing the master oscillator/ power amplifier configuration. The phase conjugator provides gain isolation and wavefront correction. The 4-pass amplifier employs passive optical switching.

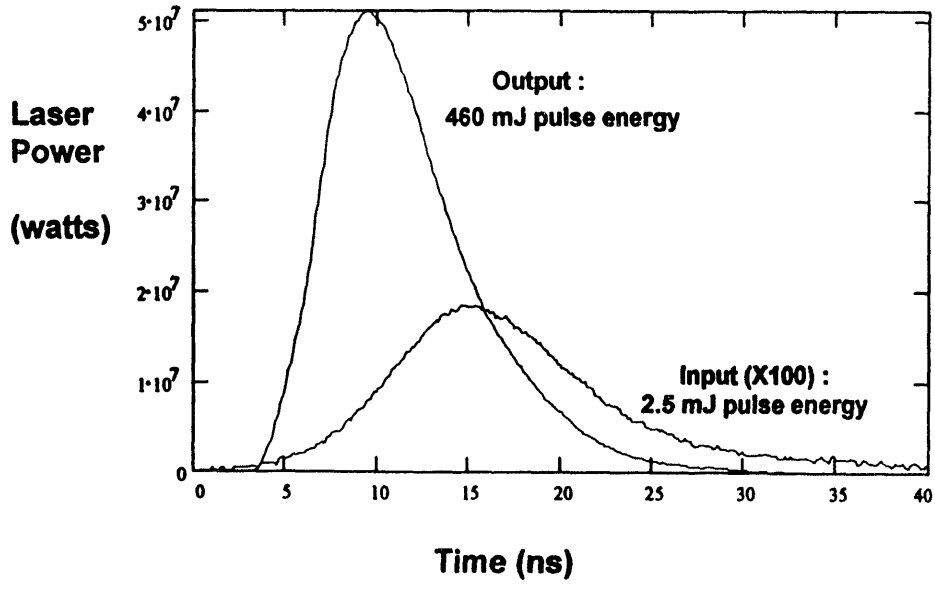

Figure 2. Typical input and output pulses for the EUV-laser operating at 460 mJ pulse energy and 7 ns pulse length.

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