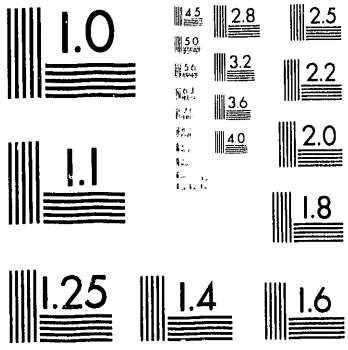
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Phase Conjugated Lasers Applied to Commercial X-ray Lithography*

Lloyd A. Hackel, C. Brent Dane, Mark R. Hermann, Luis E. Zapata

Over the last 20 years lasers have been a useful tool in the generation of x-ray radiation. Recent technology advances have allowed solid state lasers to be designed as a drive source for proximity print x-ray lithography systems as well as in the longer term for soft x-ray projection lithography systems.[1,2] In addition the ability to build multi-hundred joule per pulse, several nanosecond pulselength lasers with repetition rate capability and table top size now allow us to design table top x-ray sources and x-ray lasers.

Within our laboratory we have been building several high power solid state lasers for direct application to these systems. We find that the best performance of these high power lasers is obtained when we include non-linear phase conjugate mirrors. These mirrors function in two important respects; they provide a means to obtain very high beam brightness without the generation of hot spots which damage optical components and in addition because of their threshold activation characteristic they function in the role of multistage gain isolators. In this lecture we will describe in detail the design and performance of two systems which are being hardened for commercialization and a third system which is in the design phase and will be used as a pump source for an x-ray laser.

25 Joule per pulse Nd:glass laser; proximity print lithography source

Using a regenerative amplifier technology we have developed a phase conjugated Nd:glass laser system capable of producing near diffraction limited output beams at 25 joules per pulse and up to 5 Hz pulse repetition rate. An initial version of this laser was described at the first International School on

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Nonlinear Optics. However the present design is simpler, more tolerant of high energy pulses and operates at higher average power. In the design the laser for x-ray lithography is operated with a 12 ns pulse length. However with improved understanding of the phase conjugate mirror and the substitution of a Faraday rotator for the input/output Pockels cell the laser is successfully run in a long pulse (~ 1μs) mode. This opens up additional applications where long coherent pulselengths are desirable.

The basic design of the laser is shown in Figure 1. The laser consists of a low power master oscillator run in a self seeded mode to produce single frequency, diffraction limited output. The oscillator output is preamplified, anamorphically expanded and then imaged into the regenerative amplifier ring. The ring amplifier is configured with a polarizer and 90° rotator which act as a passive polarization switch. The input beam transits the ring once, double passing the Nd:glass amplifier (unsaturated gain of ~3/pass), rotates in polarization and passes the ring a second time (obtaining 4 gain passes). After the second ring pass the polarization has rotated to transmit the beam to the phase conjugate mirror. The energy delivered to the conjugate mirror is ~2.5 J.

Our phase conjugate mirror for this application is a two cell arrangement filled with CCl_4. In general the limit to the peak power that can be delivered to a focused SBS phase conjugate mirror is determined by competing processes such as stimulated Raman scattering, self focusing and optical breakdown. This limitation is overcome by using a two cell system configured in an oscillator/amplifier arrangement. The collimated input beam is directed through the first SBS cell and then focused into the second, oscillator, cell. In this way the peak optical power in the focused oscillator cell is reduced by the SBS amplification of the Stokes wave in the collimated amplifier cell. The beam cross section in the collimated cell is nominally adjusted such that the peak gain, irradiance, and length product (gIL) is ~30, near the threshold for stimulated return from that cell alone. It is important to operate the SBS phase conjugate mirror high above threshold to have high reflectivity and the best reproduction of the temporal profile of the input pulse.

In the present configuration of this flashlamp pumped Nd:glass amplifier system, the lamps can be pulsed at repetition rates of up to 5 Hz with 2.5 kJ deposited electrical energy per pulse before reaching the stress fracture limit of the amplifier glass. As the pulse repetition frequency of the laser system is increased, the thermal aberrations introduced by the amplifier increase significantly. Figure 2 shows a comparison of the far field output of the laser running at 75 watts output power (3 Hz) with and without the phase conjugate mirror. The unconjugated output beam divergence increases to nearly 15X the diffraction limit. However when the amplifier is configured to include the SBS phase conjugate mirror the beam quality nearly matches the 1.25X diffraction limited quality of the input master oscillator.

The laser system has been thoroughly tested with over 10^6 shots. We have designed a compact package which easily fits the allocated profile on an x-ray lithography stepper. The introduction of this laser into the commercial x-ray lithography market has now begun.

0.5 Joule per pulse diode pumped Nd:YAG laser: soft x-ray projection lithography source

We have used an appropriately scaled version of the master oscillator/regenerative amplifier technology to design a 1.3 kHz repetition rate, 7.5 ns pulselength, 0.5 J/pulse laser for use as a source driver in soft x-ray projection lithography. The oscillator is a self-seeded Q-switched Nd:YAG rod pumped by an array of laser diodes. The power amplifier is a Nd:YAG slab pumped by two large arrays of laser diodes. The amplifier is pumped to a small signal gain of 16 per pass and thus only four total passes are required. As in the previous design the amplifier is configured to use passive polarization switching with a phase conjugate mirror positioned after the second amplifier pass.

The high repetition rate of the laser is achieved from the diodes through the use of an aggressive heat rejection concept, silicon microchannel coolers. These coolers can maintain acceptable diode operating temperatures while rejecting heat at rates up to 1 kW/cm^2. Two diode bars are mounted are mounted on each package making up a unit which is approximately 1.8 cm wide. The packages are then stacked at a density of 10 packages per cm with a single water inlet and outlet. Each package requires cooling at 1 cc/s and a pressure head of 60 psi.

As a major step in completing this project, we have constructed a preprototype system using existing hardware and completed critical testing at full amplifier thermal load. The preprototype amplifier was limited to a gain of approximately 1 Np (2.7) and a total extracted energy of 180 mJ/pulse. The preprototype oscillator was flashlamp pumped and limited to a repetition rate of approximately 20 Hz. The amplifier however, was diode pumped and operated at repetition rates up to 2.3 kHz with approximately 1 pulse out of 100 extracted.

The series of tests confirmed the basic concept of the design. The extractable energy was limited by clamping of the amplifier gain due to spectral shifts in the diode wavelength and depolarization caused by stress birefringence in the thermally loaded slab. Both problems will be corrected in a new amplifier design which will incorporate proper wavelength diodes and improved thermal management.

A critically important aspect of the laser performance was the beam quality of the output under full thermal load. Significant phase aberration was noted under full thermal load for just a single pass of the amplifier. The phase

conjugate mirror however effectively corrected all the distortion even in the 8 pass preprototype configuration. Figure 3 shows the identical diffraction limited beam quality for all pulse rates from 10 Hz to 2.3 kHz.

The positive results of these preprototype experiments have reinforced our belief that the full scale prototype can be built to meet all specifications. The hardware is being fabricated and assembled. Testing will begin in the Fall.

300 J/pulse Nd:glass laser; x-ray laser driver in a table-top size

We plan to build a table top size 1 μm laser operating at 300 J/pulse and pulselengths as short as 1 ns. The laser will use a Nd:glass slab with multiple passes to achieve the required energy extraction. Efficient pumping of the x-ray gain medium requires pulse lengths as short as 1 ns. However, such short pulse lengths would induce non-linear self focusing and result in optical damage within the amplifier. Our strategy is to run the laser a safe 20 ns pulselength and use an efficient SBS pulse compression to achieve the desired short pulselength. Brent Dane will provide a detailed description of this pulse compressor in his lecture at this school.

A phase conjugate mirror will again be a critical part of the system design. It will provide the high quality beam which is required for two distinct reasons; first uniform phase supports uniform fill of the aperture and efficient extraction, and second because of the high power associated with this laser, uniform phase is required at high power to prevent damage to optical components. The high beam quality afforded by the phase conjugate mirror will also support achieving the tight line focus desired for pumping the x-ray laser.

1. L. A. Hackel, J. L. Miller and C. B. Dane, "Phase Conjugation in a High Power Regenerative Laser Amplifier System," International Journal of Nonlinear Optical Physics, Vol. 2, No 1, 1993

2. Lloyd A. Hackel, Brent Dane, Mark Hermann and Luis Zapata, "Solid State Laser Driver for Projection X-ray Lithography," presented at the Optical Society of America Soft-X-Ray Projection Lithography Topical Meeting, May 3-6, 1992, Monterey , California

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