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Advanced laser driver for soft x-ray projection lithography

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ABSTRACT

A diode-pumped Nd:YAG laser for use as a driver for a soft x-ray projection lithography system is described. The laser will output 0.5 to 1 J per pulse with about 5 ns pulse width at up to 1.5 kHz repetition frequency. The design employs microchannel-cooled diode laser arrays for optical pumping, zigzag slab energy storage, and a single frequency oscillator injected regenerative amplifier cavity using phase conjugator beam correction for near diffraction limited beam quality. The design and initial results of this laser's activation experiments will be presented.

1. INTRODUCTION

In support of an integrated soft x-ray projection lithography system being developed at the Lawrence Livermore National Laboratory, we are developing a kilowatt class, advanced solid state laser of production quality that requires (1) a peak power in the range of 50 to 200 MW, (2) pulse energy in the range of 0.5 to 1 J, and (3) repetition rates up to 1.5 kHz, to allow high volume throughput. The required pulse duration that maximizes soft x-ray production is to be found experimentally and is expected to be in the range of 1 to 10 ns. Pulses shorter than about 3 ns may be limited by nonlinear self-focusing (B-integral) damage within the Nd:YAG gain medium. In this eventuality, we propose to use stimulated Brillouin scattering pulse compression to achieve the required pulse width.

All these requirements, in unison, cannot be achieved by any existing laser. To meet the challenge, we have pulled together several advanced technologies that have proven themselves in the laboratory that are maturing into the state of the art such as a high power diode array, slab geometry amplifier, phase conjugation, etc. We made a conscious effort not to rely on untested technologies. With this philosophy built into our design, we have a high probability of success. The activation experiments show promising results. This laser, when fully operational, will pave the way to a compact, reliable, and robust source of high quality laser output at kilowatt levels with applications in many other industrial arenas.

2. LASER DESIGN

The use of diode pumping minimizes heating of the medium, thus maximizing the average power available from a given gain volume. The narrow linewidth emission of AlGaAs laser diodes matches well with the Nd³⁺ absorption bands around 808 nm, allowing for efficient coupling of diode pump energy to the upper laser level. Microchannel cooled diode bars described below have been developed at LLNL that can be stacked to provide a peak optical power of 500 W/cm² at duty factors of 25%. This performance level is proven and assures long term reliability.

The requirement to operate the laser at high average and peak power dictates the use of high optical quality crystalline host materials available in large sizes. We considered YAG, GGG, and YLF. Each of these materials has advantages and disadvantages. For example, YLF has natural birefringence that makes it resistant to thermally induced birefringence, but it has the lowest strength in this group and is not available in a size large enough to reject the average heat load required for this task without incurring a high risk of fracture. GGG has a stimulated emission cross section that allows high storage density, and it can be grown in single crystal boules up to 80 mm by 300 mm and with Nd³⁺ doping levels of up to $\sim 4 \times 10^{20}$ ions/cm³; however, it has large thermo-optic and nonlinear focusing coefficients and, since the demise of computer bubble memories (for which it was a substrate), GGG is no longer readily available. We chose YAG because single crystals to 25 mm by 220 mm can be readily obtained commercially. Its size, stimulated emission cross section, and mechanical strength are adequate for storing the required energy/power with a low risk of thermal fracture. Its nonlinear coefficient will not represent a problem unless pulses shorter than about 3 ns are required from this laser.

Our laser incorporates an oscillator and a regenerative amplifier. The oscillator produces a single-frequency output pulse, which is formatted to full spatial size prior to injection into the amplifier. The amplifier extraction architecture uses passive polarization rotation to switch into and out of a four-pass ring. A stimulated Brillouin scattering (SBS) cell placed between the second and third pass provides gain isolation and beam quality restoration. Figure 1 shows a schematic layout of the laser. A version of this concept utilizing an active electro-optic switch and eight passes through the gain medium is now successfully operating in a high-peak-power (to 3 GW) glass laser system with an average power of 100 watts in our laboratory.²

Figure 1. Schematic layout of the soft x-ray projection lithography laser system.

A pulse duration of several nanoseconds or less can lead to optical damage through nonlinear self-focusing (B-integral) of the beam within the amplifier. In order to accommodate this operational regime, the laser will be operated with a longer pulse (e.g., ~10 ns) and an SBS pulse compressor will shorten the pulse to the required 1 to 3 ns duration.

3. DIODE PUMPING

The high average power and high repetition rate required for this laser will be enabled by employing a laser diode pump with a thermally efficient method of packaging in which the diode bars are mounted on microchannel coolers.³ These coolers minimize the 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. A laser employing 160 array packages is currently pumping a 20 by 80 by 4 mm Nd:YAG slab achieving an average output power of 1000 watts.⁴

Figures 2a and 2b are photographs of our present modular diode package. Arbitrarily large 2-D apertures can be assembled by simply stacking modules using metal-impregnated (conductive) silicone rubber gaskets patterned with the same through-holes as the cooler module shown in Figure 3.

The modules of the resulting stack are thus connected electrically in series. The module shown in Figure 2 consists of three layers in a silicon-glass-silicon sandwich configuration. Figure 3a shows these three components. The top layer contains etched-silicon microchannels, which are used to supply water from the inlet ports to the microchannels just below the location of the laser diode bar. The central glass insert is slotted and has through-holes matching the silicon layers. The slot allows the water in the microchannels to flow to the output drain ports. Figure 3b shows the three pieces in a cross-sectional view and illustrates the flow path of the water. The thickness of the silicon-glass-silicon sandwich and silicone rubber gasket are approximately 0.75 mm and 0.25 mm respectively, yielding a stacking density of 10 packages per centimeter.

Figure 2. (Left) Modular microchannel-cooled laser diode package that accepts 1.8 linear centimeters of diode array. The package dimensions are 20 by 20 by .75 mm. (Right) The diode bar is mounted at the edge of a coated surface, emitting light down and toward the right of this photograph.

Figure 3. (Left) The three layers of the microchannel-cooled module. The borosilicate glass insert is sandwiched between two pieces of etched silicon—the manifold layer and the microchannel layer. (Right) Cross sectional view of the water flow.

Figure 4 shows a cross-sectional view of the microchannel region directly below the location of the bar. It is this fin-like structure and the laminar flow of cooling water through it that accounts for the unique cooling capability of the package. Figure 5a shows one of the two pump stacks employed by our laser. Each consists of 150 modules and is capable of average powers up to 3 kW optical output. We have tested to 14 kW optical peak power at 15% duty factor (2.1 kW average) and measured the average spectrum at one of the ports of an integrating sphere. Figure 5b shows this *pump* spectrum.

Figure 4. Scanning electron micrograph showing a cross-sectional view of the etched microchannels. The channels and separating walls are both approximately $25\ \mu\text{m}$ wide and the channel depth is approximately $150\ \mu\text{m}$.

Figure 5. (Left) This 150-module stack is one of the two arrays fabricated for pumping the Nd:YAG slab shown in the background. (Right) Spectrum of the 150 diode stack pump array obtained at one output port of an integrating sphere.

3. OSCILLATOR

The oscillator is designed to produce 2 to 5 mJ per pulse and is configured to operate with a single-frequency output to optimize performance of the SBS phase conjugator in the power amplifier. Twenty single-bar modules are stacked and the output is formatted to end pump a Nd:YAG rod. The fast axis output of the diode bars is collimated to 10 mrad by cylindrical microlenses developed at LLNL. The output is fed to the curved end of a quartz condenser that brings the output to the end of the rod. Figure 6 shows a photo of the oscillator pumping/cooling hardware.

Figure 6. Photograph of the oscillator showing the diode stack, focusing duct, and cooling jacket.

The single-frequency output is achieved by self-seeding the cavity using an electronic linewidth narrowing technique.^{5,6} The oscillator consists of a two-mirror resonator with a polarizer and a Pockels cell to hold off oscillation during the gain buildup. The Pockels cell voltage is adjusted to retard a bit less than quarter-wave, causing the Q-switch to leak slightly. A 25 mm etalon in the cavity narrows the gain bandwidth but cannot alone hold off the buildup of multiple frequencies after the Q-switch is opened. As the diodes are pulsed, the cavity gain increases and with the leakage properly adjusted, the lowest order longitudinal cavity mode with a frequency near the peak of the gain curve will come above threshold and oscillate. At this point, a photodiode senses the first relaxation oscillation small output reflected off the polarizer and triggers the electronics to drive the Pockels cell fully open. The low-power oscillator serves to seed the build-up of the high-power Q-switched pulse, suppressing other output modes that would otherwise build up from noise. Thus, the single-frequency mode builds most rapidly, depleting the gain and preventing the emergence of other longitudinal modes. This method produces a high quality, single-frequency output.²

4. AMPLIFIER

In order to provide the necessary energy per pulse at high average power, a slab laser geometry is employed. In addition, we must have a high average power optical switch to allow injection of the seed beam, routing to the phase conjugator, and finally switchout of the regeneratively amplified extraction beam. This can be accomplished by an electro-optic switch that, in this case, must operate at higher average power than has been reported to date. Passive polarization rotation can be used if fewer passes through the gain medium are required for efficient extraction. This means high gain and angle multiplexing through the slab. We decided to place the burden on development of the angle multiplexed laser amplifier that operates in a

storage mode with a single-pass gain of about 20 (3 Neper) rather than a high average power Pockels cell. To reach this gain, the amplifier geometry must be carefully designed to minimize losses caused by amplified spontaneous emission (ASE) and to prevent parasitic oscillation. In addition, the seeded, 4-pass, phase-conjugated, regenerative amplifier architecture shown in Figure 1 depends on a spatially uniform gain profile to operate successfully. A set of computer codes, collectively named TECATE/BREW,⁷ have been built and benchmarked against operational laser systems. These are fully 3-D theoretical models that solve for the thermal, stress, and deformations distributions for a given pumping and cooling geometry. Using them, it is possible to analyze the zigzag propagation through the medium and to compute interferograms and birefringence for the thermally loaded slab. Other codes address the more subtle issues of ASE and parasitics that impact the specific facet cut angles for the crystal amplifier. These codes have been verified experimentally and can be utilized with confidence in the design of zigzag slab amplifiers, such as the one presented here.

Because of the high average power required, the amplifier is based on a zigzag Nd:YAG slab. The nominal slab dimensions are 25 by 6 by 200 mm with a 40° wedge angle at the sharp ends. The wedge angle was chosen to minimize ASE losses and eliminate parasitic oscillation. Several slab geometry cases were investigated theoretically with our Monte-Carlo code. The results are shown in Figure 7 as pump gain (gain that would develop without ASE effects) vs. single pass gain (the observed ASE depleted gain). The code allows us to input the gain distribution within the slab and the refractive index at the six main surfaces. For the cases shown, the input/output wedges are in air and are antireflection coated; the large faces are in contact with water ($n=1.33$); the curves reaching the highest gain levels were obtained by invoking a perfectly matched index of refraction at the edges of the slab. The lower set assumes a mismatched index of 1.47 at the edges compared to 1.82 for YAG. For each set, several wedge angles were investigated. The curves end abruptly at that gain where the code found strong parasitic oscillation. In practice, the higher gain set of curves may be approached if the edge surfaces are either diffuse, closely index-matched, or coated with an absorbing layer. Figure 7 sets the possible boundaries for the performance of the actual device. A single-pass gain of 30 (3.4 Np) should be possible when a 30° wedge angle is used and if the edge surfaces are made to be absorbing. Our design baseline was a single-pass gain of 20 (3 Np).

Figure 7. Predicted single pass gain performance as function of the wedge angle of the slab, for idealized cases where the upper set of curves assumes perfectly matched index of refraction at the edges and water at the large pump faces. The lower set assumes a Uropol interface $n=1.47$ at the edges. The circles are the measured single pass gain in our slab.

The thermal performance was estimated using TECATE/BREW suite of codes. A surface source term was modeled with the same characteristics of the diode stacks; e.g., 160 discrete sources aligned over a 18 mm span and stacked 1 per mm for 150 mm, each discrete source emitting into a 56° by 12° astigmatic cone distribution peaking on axis. This defines the pumped area of the slab. The volumetric source distribution is computed by ray tracing into the discretized slab volume following the Beer-Lambert law of absorption. The result was normalized so that the total thermal power deposited corresponded to 80 W/cm^3 —the estimated high end of operation for this amplifier. Cooling boundary conditions were modeled as close as possible including turbulence development. Many possible configurations for the flow were investigated. Also, we included the estimated surface sources due to leaking ASE power that deposited heat at edges and tips. The different configurations were judged by the computed stress figures and transmitted wavefront. The design settled in a longitudinal cross-flow configuration with high cooling on the pumped surfaces, and with slab tips shielded from pump light. The slab aperture is 200 by 25 by 6.4 mm; however, the pumped area is approximately 150 by 20 mm. This means that a zone near the edges extending the full length is not pumped. The reason is that the areas of the aperture near the edges are prone to depolarization due to edge effects that are not averaged out by the zigzag propagation. Figure 8 shows examples of the temperature, stress, and deformation distributions generated. The computed interferogram of a beam making 22 zigzag traverses through the slab is also shown. These results are idealistic in the sense that, in this instance, perfectly uniform pumping and cooling were invoked. Though it is difficult to know what the uniformity of the real device will be, sensitivity runs have shown that gradients in pumping and cooling of a few percent generate measurable wavefront error at the quarter wave level. Nevertheless, experience has indicated that the phase conjugator can correct for up to several waves of residual distortions generated by the real device.

Figure 8. Representative TECATE/BREW code results for the Nd:YAG slab of our design. The scale factors in a, b, and d expand the thin dimension for clarity:

- a) Temperature distribution in a cross section perpendicular to the slab axis through the slab center. Isotherms are 3° apart.
- b) Stress contours in longitudinal cross section through the center of the slab. Six MPa contours go from about 50 MPa tension on the surface to 25 MPa of compression in the midplane next to the pumped/unpumped transition.
- c) Deformations magnified 3000 times.
- d) Single-pass interferogram for the 22 bounce zigzag path of the extracting beam (one wave contours).

It is an engineering challenge to achieve pumping and cooling uniformity to within a few percent. With respect to the diode laser pump, we have measured a uniformity within 3% for the *new* diode stacks we are now using. However, in other stacks that have been heavily driven, we have measured non-uniformities (hot and cold spots) of 20% or so. To alleviate this problem, we will be driving our stacks at lower current levels than has been the *standard* for LLNL packages (e.g., ~100 A instead of 120-140 A). Because of the modular nature of the diode packages, the packing density and possibly the current to individual sections of diodes could be adjusted to achieve the required uniformity. The slab cooling is achieved by water flow along the large slab faces. The uniformity of the slab face temperature is dominated by the surface heat transfer in the cooling

channel. Ideally, the heat transfer is rapid enough that the slab face temperature uniformly approaches that of the cooling water. In order to achieve this condition, the viscous boundary layer in the flow channel must be minimized; that is, the flow should be fully turbulent. The water in the supply plenum for the channel is laminar and needs to have changed to highly turbulent before contacting the slab faces. A key feature of the design, therefore, will be a sufficiently long transition section with appropriate flow *trips* to ensure that full turbulence is achieved as the flow first contacts the slab face. The combination of uniform pumping and face temperature will provide an amplifier with uniform gain and minimal induced phase aberrations. A schematic of the assembly diagram is shown in Figure 9.

Figure 9. Assembly diagram for the amplifier head showing the major components.

5. OPTICAL EXTRACTION ARCHITECTURE

The 5 mJ oscillator output is amplified to 1 J 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 in minimizing the potential for optics damage caused by the fidelity return from the phase conjugator. A schematic layout of the optical architecture is given in Figure 1. Since the conjugator is a nonlinear threshold device, it acts as an isolator of amplified spontaneous emission between stages. The phase aberrations accumulated in the amplifier, as the beam propagates to the conjugator, are reversed in the conjugator and are then canceled in propagating back out, producing a nearly diffraction limited output beam at high average power.

A similar amplifier configuration has been extensively tested using a flashlamp-pumped 1 by 120 by 400 mm Nd:glass slab.² With a single-frequency input of 40 mJ from a master oscillator, an output of 25 J per pulse at 12 ns pulse length with near diffraction limited beam quality is routinely obtained. Limited by the fracture strength of the glass, this system presently generates an average power of about 100 watts. With the increased thermal conductivity and strength of the crystalline YAG

slab, and with the reduced quantum defect of diode pumping, this average power capability should be increased to the kilowatt range.

6. EARLY RESULTS

At this point in time, we are nearing the full dress rehearsal for this laser. As usual, minor problems have surfaced as we debug all the systems involved. However, we can already claim success in a number of areas: The diode stacks have been tested at 14 kW optical peak power, 2.3 kW average optical output power. The wavelength dependence on duty factor was characterized and the uniformity was measured. The oscillator has performed at 300 Hz, 3 mJ, single frequency and is presently being upgraded for 1 kHz operation. The amplifier gain was measured and was found to perform as expected (see Figure 7). The optical extraction architecture has been tested end-to-end at 1 Hz and the extracted beam obtained was nearly diffraction limited, 0.5 J at 10 ns pulse width. We are now awaiting the completion of the cooling system before high repetition rate experiments can begin.

7. SUMMARY

The high-average-power laser we are building for the x-ray projection lithography system has requirements surpassing currently available laser systems. Furthermore, it incorporates concepts and components whose performance we have individually demonstrated in our laboratory. This design includes: (1) high-average-power output from a diode-pumped crystal, and (2) high beam quality and efficient extraction using our master oscillator/regenerative amplifier optical architecture. During the remainder of this year, we will finish the construction and test the performance of this laser subsystem and then integrate it into a soft x-ray projection lithography system. It is anticipated that the laser will meet all the requirements for the x-ray source driver and help bring soft x-ray projection lithography into commercial production near the turn of the century.

8. ACKNOWLEDGMENT

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