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Technical challenges for the future of high energy lasers

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ABSTRACT

The Solid-State, Heat-Capacity Laser (SSHCL) program at Lawrence Livermore National Laboratory is a multi-generation laser development effort scalable to the megawatt power levels with current performance approaching 100 kilowatts. This program is one of many designed to harness the power of lasers for use as directed energy weapons. There are many hurdles common to all of these programs that must be overcome to make the technology viable. There will be a in-depth discussion of the general issues facing state-of-the-art high energy lasers and paths to their resolution. Despite the relative simplicity of the SSHCL design, many challenges have been uncovered in the implementation of this particular system. An overview of these and their resolution are discussed. The overall system design of the SSHCL, technological strengths and weaknesses, and most recent experimental results will be presented.

Keywords: laser beam control, wavefront control, adaptive optics, high energy laser, solid-state lasers, directed energy, DPSSL

1. INTRODUCTION

Since the inception of the laser nearly half a century ago, the desire to achieve higher output powers out of smaller footprints has driven a large effort in a variety of technical areas from pulsed-power, to efficient, high-power diode lasers, to transparent ceramics. The advent of high-power, efficient diode pump sources in particular has ushered in a renaissance in high-power laser system designs having efficiencies in the double digits. The advances have not just been in the solid-state arena, diode pumping is being applied to gas and liquid lasers as well.[2,7] Diodes are not being used just in bulk solid-state lasers. Some of the highest overall efficiencies have been achieved in guided solid-state gain media (i.e., fiber lasers[5]).

Despite recent advances, the development of high-power, solid-state lasers for military applications is still in its infancy. Lasers such as ABL and MTHEL have been proposed for air-to-air and surface-to-air missile defense, land mine mitigation and improvised explosive device (IED) neutralization.[6] At typical operating wavelengths around 1 micron for solid-state lasers, propagation characteristics and target interaction dynamics are not well known. Therefore, the required laser output energy for particular applications is not known. 100kW has been put forward as the threshold power required for the majority of proposed applications. But, that is an estimate based largely on models of atmospheric propagation and laser-target interaction benchmarked against data from other wavelengths or power levels. Some experiments already have performed using the LLNL's SSHCL to improve the understanding of atmospheric propagation and laser-target interaction. Integrated experiments of land mine mitigation have been performed but at the current power levels and estimates for the number of landmines world wide, it would take over 300 mitigator*years to neutralize all land mines. The experimental databases for the areas of largest uncertainty need to be grown.

With existing systems capable of producing several 10's of kilowatt, the ability to experimentally evaluate the propagation of high intensity 1 micron energy in nearly in-hand. The White Sands Missile Range (WSMR) and LLNL's Site 300 have outdoor facilities capable of supporting not only one these existing laser systems on a mobile platform but also a variety of propagation scales and geometries as well as live targets. The effort just needs to be put forward to install the systems and begin performing experiments.

In the area of target interaction, LLNL is currently working on comparable and actual target materials in a variety of interaction scenarios. But much more needs to be done. The argument has been made that lasers will not work for a variety of applications because the mitigation of laser damage is so trivial: coat the device with white paint, a mirror or, better yet, a retro-reflective material thus redirecting the laser energy back onto itself and effectively destroying it. That would be true except for the fact that every material has a damage threshold. How high can the damage threshold be? White paint is roughly 90% reflective (diffusely), metallic mirrors can be 96-98% reflective (the rest of the energy being absorbed) and dielectric mirrors can be in excess of 99.8% reflective. There are several disadvantages of dielectric mirrors not the least of which are their directionality and fabrication requirements. Dielectric mirrors are, in general, directional. They can be fabricated to work over a wide spectral and angular bandwidth. But, this in general increased the cost and complexity of fabrication. The fabrication requirements for a hard, high-damage-threshold coating are already daunting. It requires precision controlled vacuum deposition facilities. To evaluate the efficacy of a laser on a particular target, a point design for the laser mitigation scheme must be established. A reasonable value, achievable at low cost, without specialized hardware or materials is ~98% reflective (2% absorbing). For a 100kW laser, that is 2kW of absorbed power. At what intensity does that 2kW overcome the damage threshold of the mitigation technique? It turns out that for paint, the damage threshold can be overcome in the range of 10s of Watts per square centimeter. So, for a 100kW laser depositing just 2% of its energy in a 20 square centimeter area, the damage threshold can be overcome. And, once it is, burn through and destruction of the target can be accomplished quite rapidly.

Target interaction and propagation studies must be performed in parallel with the current developments in DPSSL system designs. If not, premature down-selection could result in an inappropriate system built for an ill-defined application space.

Recent advances in wavefront control on the SSHCL that take advantage of clean, low absorption materials and coatings, passive polarization control, an increased number of control points and pumping uniformity have increased run time, and hence total deliverable energy, by greater than a factor of 20 in less than 6 months. Even at a more sustainable pace, DPSSL's will achieve the 100 kW milestone in a matter of a few years. The progress towards this goal an a discussion of the universally relevant issues encountered along the way are presented below.

2. HIGH ENERGY LASER SYSTEMS

2.1. The rise of the DPSSL

Solid state lasers still have yet to demonstrate scalability much beyond 50kW (with SSHCL) (and that for a limited run time of only a few seconds) but hold the promise of scalability to the same power levels as chemical lasers. To date, chemical lasers such as MTHEL, MIRACL and TRW's ALPHA lasers, have achieved the highest overall power levels. Despite their high powers, they have, of late, fallen out of favor in lieu of their solid-state counterparts. One reason is the logistical difficulty in supplying the fuel, especially in a mobile implementation. Some require the transportation of tanker trucks containing caustic materials such as gaseous chlorine and a hydrogen peroxide solution of potassium hydroxide (lye). (chemical oxygen iodine lasers (COIL)) or at least hard to come by materials like deuterium (deuterium-fluoride (DF) lasers). And, some have byproducts such as hydrofluoric acid (DF lasers). Solid-state lasers, on the other hand, are ultimately electrically powered. And, with the use of diesel generators, hold the promise of being operable on a mobile platform within the framework of the existing logistical infrastructure. Diesel exhaust would be the most caustic byproduct. One of the more important factors that boosts solid-state lasers is that they are also more efficient. So, they not only use less exotic fuel, but they also use less of it. Higher efficiency also has the beneficial side-effect of reducing the heat footprint of a system of a given size. A smaller heat footprint not only simplifies the dissipation of waste heat but also makes the system harder to detect. But, the most important effect of higher efficiency is the effect on the optomechanical system itself. With smaller heat flux into and out of the laser, the system will be more robust. For the same average laser power, components can be operated further from their fracture limit. Similarly, wavefront correction becomes easier with smaller thermal gradients. Given unfettered choice of and control over the laser materials, there is no fundamental reason why a solid-state laser system cannot be constructed with a wall-plug (electrical-to-optical) efficiency arbitrarily close to 100% efficient. The ability to approach high efficiency will ultimately determine the success or failure of solid-state lasers for high power applications.

2.2. LLNL-DPSSL system design

A variety of different designs are being investigated for high power solid state laser systems. All include diode-pumping because of the tremendous benefit to overall efficiency. Diode pumping is conducive to gain media with narrow absorption bands such as those with crystalline hosts. Many host materials and host/active ion combinations have been considered and are still under investigation. But crystals are limited in the size and rate at which they can be fabricated. There has been much interest, lately, in transparent ceramics that have comparable and, in some cases, better performing properties (such as the fracture toughness) as their single crystal counterparts. The difficulty is in producing truly optically transparent ceramic materials. This means low scattering in the 100's of parts per million per centimeter of propagation and low absorption by impurities.

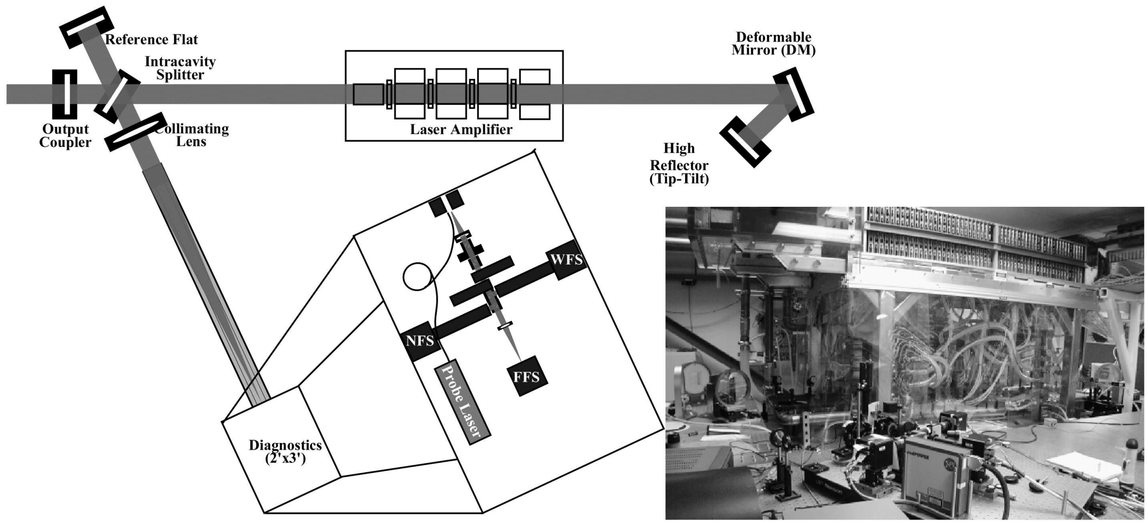

Figure 1. Schematic diagram of the diode-pumped, solid-state laser (DPSSL) at LLNL and photograph of hardware (inset). An intracavity, adaptively-corrected, unstable resonator facilitates an elementary design. It is less than 5 meters on its longest dimension and fits on a single optical breadboard. Space is available for the inclusion of additional gain media whose total volume scales linearly with the output power. Unlike many other (e.g., aperture-multiplexed) high-power DPSSL designs, the wavefront error also scales just linearly with power.

For a more detailed description of SSHCL, see ref.[3] A brief description is included here. SSHCL employs a Nd:YAG ceramic gain medium. The gain medium slabs are off-normally, face-pumped at 808 nm. The slab/pump geometry is modular to allow for more slabs to be inserted to scale to higher power. The the laser power nominally scales linearly with the volume of gain medium. It is configured in an unstable resonator geometry with an intracavity deformable mirror (DM) detailed below. The slabs are not actively cooled to minimize thermal gradients and hence thermally induced wavefront errors. In the ideal case in which the slabs heat up uniformly, the thermally-induced phase delay is not a function of the location in the pupil. Such a “piston” error is transparent to the performance of the laser, changing the optical path length of the cavity imperceptibly. Therefore, large temperature excursions in the slabs can be possible without deteriorating performance. The heat load is not, of course, uniform. The effort is then to keep the level of nonuniformity within the temporal, spatial and amplitude range of the correction system.

2.2.1. The heat capacity concept

The heat capacity laser concept developed at LLNL was founded on the principle that if heat did not need to be extracted from a [solid-state] laser, a more powerful laser can be build in a much smaller footprint, and done so more economically.[1] A 100kW laser that is, say 16% efficient that needs to be able to operate indefinitely, needs to be able to dissipate over half a megawatt of waste heat in real time. A heat pump with that capacity would more than double the size of the system it was trying to cool. If a finite run time is an option, then a thermal reservoir may be used. A convenient medium for a thermal reservoir is water at it’s solid/liquid phase change. Since energy is added to a phase-change reservoir without changing its temperature, the chilling cycle does not have to actively control the temperature. For a similarly characterized laser as described above and assuming a nominal operating time of 5 minutes, 470 kg, or over 1000 lbs., of water would be needed to extract the over 150 MJ of waste heat.

Unfortunately, even in the most state-of-the-art solid-state systems existing today, there has to be some level of real-time heat extraction. In particular, the diode laser pump need to be cooled in real time. Because laser diodes have a temperature-dependent output wavelength, they need to be under tight temperature control for the duration of operation. Until the development of higher efficiency diodes, this will be the largest component of the heat dissipation required in a system. And, it has to be done in real time.

The portion of the SSHCL laser that is able to operate in the heat-capacity mode is the gain medium. In the current generation, the gain medium is Nd doped transparent ceramic YAG, a polycrystalline material with similar optical properties to, more robust mechanical properties than and fewer manufacturing difficulties than single crystal YAG. The search is ongoing for other transparent ceramic host materials that have similar mechanical characteristics or may be even more robust but have more desirable optical characteristics such as a smaller quantum defect. A smaller quantum defect will not only increase the overall efficiency of the system but will also decrease the amount of heat deposited in the gain medium for a given output energy, thus increasing run time.

Operating the gain medium in heat capacity mode does not just provide benefits to the heat dissipation subsystem by reducing its load. Separating the cooling of the gain medium from the lasing of the gain medium greatly reduces the complexity of the system. Active cooling of the gain medium does not necessarily imply interfering with the optical path. But, it is often considered convenient to do so. Heat-capacity lasers benefit from fewer the elements in the optical path. Not passing a coolant through the optical path or vice-versa greatly reduces the aberrations that will eventually need to be compensated. With gain media in the heat-capacity mode, thermal gradients are also minimized, thus further minimizing aberrations.

The primary limitation of the heat-capacity design is its fundamental principle. The gain medium can only be run a finite duration before it needs to be allowed to cool. The current generation is optimized for engagement scenarios that require less than or equal to about 10 seconds of run time. Alternate point designs have been considered that increase run time or average power. To first order, the total energy output of the system is proportional to the volume of the gain medium. Therefore, increasing the number of slabs or their individual size by a factor of N, will enable the system to run N times longer, or at N times the average power, or, more generally, N times the product of the two. In fact, it has been demonstrated on the SSHCL that the ratio of run time and power can be changed in real-time as necessary for a particular application. This scaling law has held true up to the current integrated output energy of 250 kJ. Extrapolating another 1.5 orders of magnitude beyond current system performance, a 1MW system would need approximately 32 liters of gain medium or just a little over 1 cubic foot per 10 seconds of operation.

The ultimate solution to limited run time is to use a gain medium that has good mechanical properties but also optimal optical properties (i.e., a small quantum defect, low non-radiative decay cross-section, etc.) Several near-term solutions have been proposed and demonstrated all of which maintain the benefits of keeping the cooling phase separated from the lasing phase. All solutions involve having duplicate gain medium slabs and sliding or rotating them into the oscillator until they reach maximum temperature and then removing from them the oscillator path to cool them.[8] It has been shown that 2 cm thick slabs can be cooled to ambient temperatures in less than 1 minute. Because of the asymptotic nature of the cooling process, slabs can, for example, be cooled half way to ambient in much less time (about 12 seconds). With such thermal characteristics, full duty cycle can be achieved with a magazine depth of just 3 or 4 slabs. Also, since the laser is a pulsed laser (500 microsecond pulses at 200 Hz), slabs can be switched in and out without any interruption in average power. The AO system on the SSHCL system has been shown to be able to, without any special preparation, compensate for the introduction of new optical elements within the oscillator cavity. It has even been shown that with knowledge of the thermal history of hot slabs, even if highly aberrating, the system can accurately predict the required correction. With such capability, a set of slabs could be run until their heat capacity has been exhausted or the mission has been completed, whichever comes first, or the slabs could be continuously cycled.

No matter what the solution, the run time will ultimately be limited by the same thing as all other high power DPSSL designs: thermal management. All systems need some way of dissipating the waste heat in real time or storing it for dissipation at a later time. Therefore a common goal to all is to minimize the waste heat.

2.2.2. Intracavity adaptive optics

The intracavity, adaptive-optic resonator (see Figure 1) is built on the third-generation, solid-state, heat-capacity laser at LLNL. The geometry is a positive-branch, confocal, unstable resonator with a magnification of 1.5. The clear aperture within the resonator is a square 10 cm on a side. The output profile is therefore a square annulus with inner dimensions of 6 2/3 cm on a side. The wavefront must be measured and controlled within the whole 10 cm by 10 cm area. A beam-splitter is used within the cavity to couple out the full beam profile to the diagnostics. There are far-field sensor (FFS) and near-field sensor (NFS) diagnostics to quantify the performance. A Shack-Hartmann wavefront sensor (WFS) is used to measure the gradient of the phase. The WFS is simply a rectangular lenslet array mounted in front of a monochrome CCD camera with the necessary speed and noise characteristics. The gradient of the phase is sampled on a 19 by 19 grid. This is oversampled relative to what is necessary for accurate reconstruction of the wavefront within the correctable spatial frequency band of the DM. The redundancy of the oversampling provides the opportunity for additional noise reduction and diagnostic capability. Note that the average phase within each sampling interval (each laser pulse) is measured. In general, aberrations with time scales faster than the pulse duration cannot be measured or taken into account. They would have the effect of blurring the WFS or FFS images. Fortunately, careful analysis of the diffractive features of these images shows negligible blurring. A time history of all shots and their operating conditions is kept. It is used to build a predictor table for the prompt distortion or difference observed between subsequent pulses. The sensor was designed for a sensitivity of < lambda/10. The deformable mirror (DM) is designed to work with the WFS to compensate for the measured aberrations. Manufactured by Xinetics Corp., it has a ULE face-sheet, supported by 206 PMN actuators on a pseudohexagonal grid with a nominal 1 cm actuator spacing. It was designed with a dynamic range of 10 microns, larger than the maximum observed aberration occurring in the system during its designed run time. There are 126 actuators within the clear aperture of the laser except during some of the experiments with the additional focus corrector as described below. It was manufactured to a tolerance of < lambda/50 RMS powered figure. High tolerances are required on the surface quality of an intracavity DM than for one that is used in a single-pass configuration because the aberrations compound on the multiple round-trips. The DM has a high-damage-threshold, high-reflectivity, multilayer-dielectric coating. The WFS is calibrated with an off-wavelength probe laser at 1090 nm. First, the probe laser is collimated to the desired precision for the output beam. Then it is sent directly to the WFS, bypassing the cavity, to establish the WFS response to the reference wavefront. Then the probe laser is propagated one round-trip through the cavity. Each actuator on the DM that is within the clear aperture is actuated, one at a time. The WFS response to each actuator push is recorded to generate a system matrix. From all of the impulse response measurements, a matrix is built that applies a least-squares fit of the DM surface to any measured wavefront error.

3. TECHNICAL CHALLENGES

3.1. System efficiency

The primary consideration for any design decision is its impact on system efficiency. All efforts on high energy DPSSL's have high efficiency goals. One approach may have certain aspects of its design that are conducive to high efficiency. But, the same approach inevitably will have trade-offs, such as high peak fluences that introduce additional challenges to reach high powers.

Fortunately, there is much collaborative work being done to increase the efficiency of any DPSSL design. The most notable of which is the effort to design and construct more efficient high-average-power laser diodes for pumping funded by DARPA.

Part of the equation of overall system efficiency is how effectively the laser system can deliver its output to the designated target. For many industrial applications, the target may be close to the laser and propagation characteristics may not be an issue. But, for many desired applications, most notably directed energy, low-divergence, free-space propagation is a desired characteristic. To achieve this, spatial coherence, or high wavefront quality, of the source is paramount. Once system efficiency has been addressed, the next most pressing issue is wavefront quality.

3.2. Wavefront quality

There are multiple approaches to ensuring good wavefront quality in a high-power laser system, from passive ones like nonlinear phase conjugation or phase locking, to active ones like multiple aperture phasing or adaptive-optic control loops. There are merits and limitations to all approaches. It is beyond the scope of this discussion to address all of them. Herein is contained a thoughtful discussion of the issues particularly relevant for the adaptive-optic approach. For the remainder of this discussion, adaptive optics (or AO) will be used synonymously with wavefront control or correction.

First, build a laser that doesn't need AO. And then, add the AO. No design should be considered if it has an *ab initio* wavefront control requirement. In high power laser systems, it is all to easy for thermal effects to drive the uncertainties in the mechanical distances and optical path lengths to values 3, 4 or more orders of magnitude larger than the tolerances required for effective propagation. It is a challenge to construct a wavefront correction system that has a precision less than 0.1% of its dynamic range. If a system is designed with the crutch of a wavefront correction system in mind, it will be crippled by it. AO systems have been demonstrated to have to ability to improve wavefront quality by orders of magnitude. Such success has prompted the optimists to prognosticate that "the AO system will take that out." Sight should not be lost of the tolerances that must be met. And, an effort should be made at every level of system design to meet them.

Wavefront quality is a major challenge for any of the approaches including, incidentally, fiber lasers. Fiber lasers can be built in single mode fibers. Such lasers have no transverse phase information, and therefore no wavefront errors.

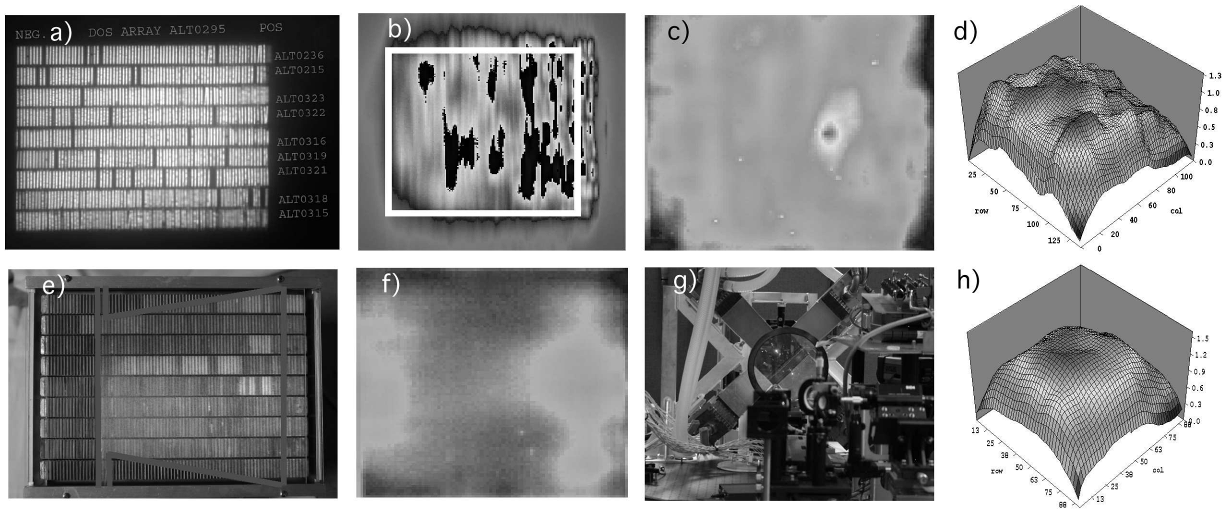

Figure 2. Optimization of the pumping geometry for homogeneity and coupling efficiency is critical to the performance of any laser system. High average power laser diode arrays are costly. If homogeneous radiance profiles are required, they can become prohibitively so. Diode arrays with nearly homogeneous radiance profiles (a) produce suboptimal irradiance (b) and thermal (c) profiles in a face-pumped geometry resulting in wavefront distortions with large, high-spatial-frequency components (d). It has been demonstrated that by homogenizing the diode array output with holographic diffusers (e) much more uniform thermal profiles can be achieved (f) with minimal losses in coupling efficiency. With lower amplitude, high-spatial frequency aberrations, laser performance is increased. The decrease in coupling efficiency is compensated by a net increase in deliverable energy. A more efficient coupling technique, edge-pumping (g), imprints an even smoother wavefront distortion (h). The distortions are primarily quadratic in nature and can be compensated for almost entirely with a dedicated focus corrector separate from a higher-order AO control system.

Unfortunately, the power in any one fiber is limited by peak fluences to levels well below the desired 100 kW design threshold. Therefore, it is necessary to phase multiple fibers together. Whether one does this by phase locking or wavelength multiplexing or by some other method, this is essentially a wavefront control issue and similar considerations apply.

3.2.1. Characterizing the wavefront error

Before any effort is expended to correct the wavefront error in a laser, the best effort should be put forward to characterize the error. The preponderance of data on the spectrum of wavefront aberrations is on those of the atmosphere and optical surfaces. Both of these have a power law dependence. The lowest order aberrations have the highest amplitude. And, the amplitude of the aberrations decreases exponentially as the spatial frequency increases. For dynamic systems like the atmosphere, the lower order aberrations also move more slowly than higher order ones.

Because laser designs are more varied in nature than the atmosphere or optical fabrication techniques, their aberration spectrum is less well understood. In general, little can be assumed about their temporal and spatial characteristics. If the aberrations are thermally driven, then a band limit on one or both characteristics can be established.

The temporal characteristics of the wavefront error depend upon the mechanism that causes it. Unlike the atmosphere, other nonlinear effects besides thermal ones can plan a significant role. Mechanical correction with, say, a DM is limited to 1’s or 10’s of kilohertz and therefore is only useful on the slower, thermal effects. Care must be taken when designing the system not to introduce conditions conducive to the evolution of fast nonlinear effects.

The spatial bandwidth of wavefront error need not be limited. This is a problem for AO wavefront correction schemes. The sensor and corrector are fundamentally band-limited devices due to their discrete sampling. And, DM’s have larger stroke capability, the lower the spatial frequency of the correction, just like the atmosphere.

In the LLNL SSHCL, pump-induced inhomogeneities in the thermal profile in the gain medium are the dominant source of wavefront errors. Due to the current limitations of high-power laser diode array design, it is difficult to obtain sources with uniform radiance profiles. Non-uniform sources, in a face-pumped geometry, imprint their inhomogeneities onto the thermal profile across the aperture of the laser. If thermal diffusion is not great enough to smooth out these

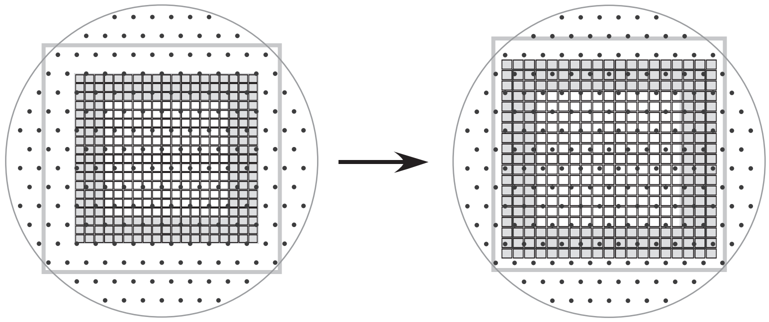

Figure 3. Registration mapping of the wavefront sensor (WFS) onto the deformable mirror (DM) before (left) and after (right) implementing the off-loaded focus corrector. The WFS has a 19 x19 square array of lenslets. The DM is 15 cm in diameter with actuators on a pseudohexagonal pattern with 1 cm spacing. The WFS is oversampled on the DM. A judicious choice of magnification of the focus corrector permitted more substantial use of the DM surface. With 20% more degrees of freedom, performance as measured by run time was increased by more than 20%.

inhomogeneities, then aberrations of the wavefront result. In earlier experiments on the SSHCL, some component of the aberrations remained at higher-than-correctable spatial frequencies. Homogenization of the pump with holographic diffusers (see Figure 2) and increasing the effective actuator spacing (see Figure 3) both helped to reduce the residual uncorrectable wavefront aberrations. Both are also a temporary solution. The holographic diffusers did increase the run time of the system by about a factor of 3. They did, however, decrease the coupling efficiency of the pump to the gain media, reducing the laser output power. Coupled with the increased, run time, there was a net gain in total deliverable output energy of about a factor of one and a half.

A poor choice of laser geometry could result in large-amplitude, high-spatial-frequency errors. Recover from a poor design choice can be daunting and radical changes to the design, such as the pumping geometry(see Figure 2), may be necessary. Simply adding more degrees of freedom to the corrector to compensate, will have the detrimental effect of reducing its stroke. That is unless a discontinuous corrector is used. Discontinuous correctors essentially unlimited stroke in a laser system because the monochromaticity permits wrapping of the phase (i.e., adding or subtracting integer multiples of 2*pi to the phase to stay within the dynamic range of the corrector). The caveat with discontinuous correctors is, of course, the greatly reduced damage threshold at the discontinuities both from fabrication errors and from enhanced electromagnetic fields that tend to form around sharp features. Mode-media interactions can introduce high spatial frequency aberration that are limited only by the diffraction feature size. This could prove problematic for high Fresnel number cavities like most unstable resonators.

A corrector will always be introducing aberrations due to the residual ripple at uncorrectable spatial-frequencies. One must consider the effect of aberrations at this spatial frequency on the performance of the overall system.

The SSHCL AO system has been able to draw from the expertise of the astronomical AO community. It employs a method to filter out the uncorrectable spatial frequencies so the don't alias on the discrete detector or otherwise frustrate the performance of the control loop.

3.2.2. Low-order aberrations

One of the first complexities introduced to any conventional AO system is to off-load tilt correction from the deformable mirror (DM). There are multiple reasons for doing this. Primarily, it is easy. Tilt correction could be performed at virtually any other optical element in the beam path, even at a lens if the corresponding influence on higher-order aberrations is taken into account at the DM. Secondly, doing so reduces the stroke requirement on the DM, increasing the systems overall dynamic range. Thirdly, a tilted mirror can more accurately represent a sloped surface than the face-sheet of a DM nominally connected at discrete points. A tip-tilt control loop, separate from the higher-order control, has been successfully implemented on SSHCL. The sensing input is gathered from a common wavefront sensor (WFS). The tip-tilt information is extracted from the WFS measurement and sent to a separate reconstruction algorithm (from that of the DM) to determine the correction that is applied to an end mirror of the unstable resonator cavity.

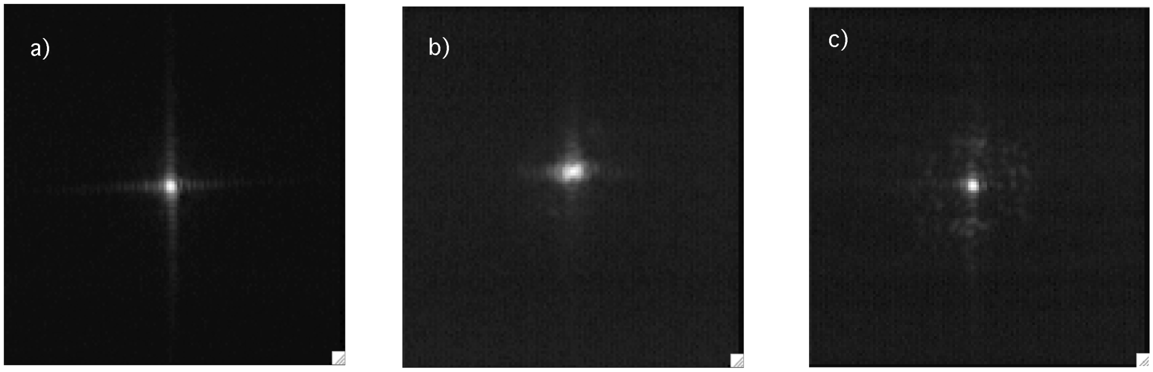

Figure 4. Stress-induced depolarization in the gain medium can degrade laser performance as measured by a probe beam (b) relative to a polarized reference (a). Since the LLNL DPSSL does not operate in thermodynamic equilibrium, the thermally-induced stress is time dependent. A passive method was employed to compensate for not only the static stress-induced depolarization but also the dynamic depolarization.

Similarly, the next step would be to offload focus correction by translating one or more powered optics in the system. For a laser resonator, the most naive implementation would involve the translation of one of the end mirrors of the cavity. This would preclude the need to employ additional optics. Unfortunately, for the SSHCL system, it was estimated that a cavity length change of over one meter would have been required to have the desired stroke. A much less elegant, but, in fact, more versatile approach involved designing and constructing a zoom lens apparatus, a defocusable telescope with infinite conjugates, that sat within the laser cavity. Such a solution provided the fortuitous opportunity to explore yet another parameter space, the number of degrees-of-freedom. For the zoom lens to have the desired positive and negative stroke, it was designed with greater than unity magnification. Strategically placing it in front of the DM, the system was able to employ more of the surface area of the DM and, hence roughly 20% more actuators (see Figure 3). Reversing its orientation caused the system to employ 20% fewer degrees of freedom. Being able to control a larger fraction of the aberration space than usual, provided the unique opportunity to experimentally probe a previously uncorrectable spatial frequency band. Given infinite knowledge of the spatial frequency content of the error, performance could be predicted for a given correction spatial bandwidth. Short of that being available, a scaling law could be derived from experiments on the SSHCL. The duration for which the laser system was able to achieve < 2 xDL performance is roughly linearly proportional to the number of degrees of freedom. Run time on SSHCL was increased by over 30% by increasing the number of actuators by that proportion.

3.2.3. Polarization control

An often underestimated component to overall wavefront quality is polarization control. In a conventional AO system, the distorted wavefront is considered to be pseudo-monochromatic and a scalar quantity. For astronomical applications, it is reasonable to assume a scalar wavefront since the atmosphere is, to a very good approximation, not birefringent. The approximation that the distortions are achromatic is not as accurate. But, for most situations, the observational band is sufficiently narrow and extremely high contrast ratios are not required. Only in the realm of high contrast applications like extrasolar planet imaging[4]and where spectroscopic information (e.g., hyperspectral imaging) is desired that the spectral width becomes problematic.

Solid-state lasers, on the other hand, are highly monochromatic. And, they do operate under conditions that are highly anisotropic. Larger effects are observed in crystalline gain media. The stress induced depolarization is higher in crystals than in glasses. The SSHCL design was chosen with depolarization in mind. The gain media are oriented normal to the direction of propagation as opposed to the more common orientation at Brewster's angle. Aside from solving a number of other unrelated issues, normal orientation does not favor one polarization over another. This is not just a convenient feature but a necessary one. The wavefront, which now must be characterized as a vector field, will get rotated as it propagates through the cavity. The direction and degree of rotation is not a constant but a function of the pupil coordinate of the laser beam. In other words, the whole beam does not get rotated uniformly. If the oscillator had been designed to be lossy to s- or p-polarization, then, as the vector wavefront propagated through the cavity and the directions of polarization were scrambled, the laser would not have enough gain to overcome the losses and would not lase at all. The

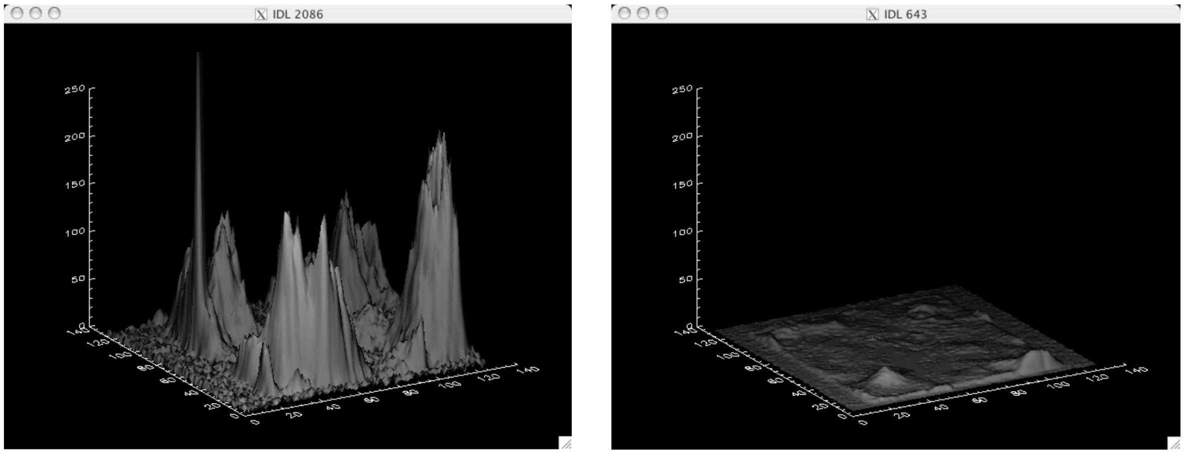

Figure 5. Stress-induced depolarization in the gain medium after one second of operation. On the same vertical scale, the degree of depolarization before (left) and after (right) passively compensating for both the static and dynamic components of stress-induced depolarization.

orthogonal polarizations for the cavity are not the degenerate s- and p-polarizations but something more complicated. Depolarization in the oscillator can be thought of as introducing an additional delta wavefront error between these two orthogonal polarizations on top of the overall wavefront error. To correct the wavefront aberrations of the laser would mean correction of both orthogonal polarizations. To do so, two DM's would be required and a beam splitter that has the appropriate coordinate-dependent polarization separation would need to be constructed. If constructed, such a polarizing beam splitter could be used to polarization the laser, it would just not be a linearly polarized laser in the conventional sense.

Because of the elegance of its design, the SSHCL system was able to use a much simpler approach to solving the depolarization dilemma. Even though it is an unstable resonator and rays do not strictly repeat their own paths after each round trip, the optical path difference (OPD) between subsequent passes through the amplifier are close enough to be considered negligible. Also, the symmetry of the pumping geometry imprinted a similar depolarization pattern on one half of the slabs as the other half. These two approximations to similar path errors allowed us to implement similar polarization unwrapping scheme that have been used in oscillators or power amplifiers. Strehl ratio increases greater than 4x were achievable with our rudimentary implementation of polarization control. This brought the SSHCL system performance close to that of a conventionally polarized approach.

3.2.4. Mode-media interactions

The pump diodes will impart a thermal signature on the gain medium in the cavity. This is to be expected. This is what is characterized and optimized for minimal thermal gradients. Also, this thermal behavior is linear. There is no feedback. There are a number of other sources of thermal gradients, some of which have positive feedback.

A variety of different samples were investigated in the output-coupled beam of 25 kW stable resonator at 2 x 2 cm (or about 6 kW/cm^2) with an thermal IR camera and a high resolution WFS (Phasics) simultaneously. Experiments in Nd:YAG show negligible re-absorption in our samples, say from impurities like iron, at the lasing wavelength (0.1 deg/sec). So, as yet there is no evidence of mode-media interaction within the Nd:YAG. Note: because the dn/dT nonlinearity is positive, any heating from intensity fluctuations would have positive feedback and cause self-focusing. The temperature rise in the gain media is dominated by heat deposition from the pump. Wavefront errors are due solely to non-uniform pumping. Results in Fused Silica were similar to the gain medium (i.e., negligible (0.1 deg/sec) especially on uncoated samples). Absorption in standard optical glasses like BK7 was too high. And, given the sign of dn/dT, it causes positive feedback for rapid aberration growth. At intracavity fluences, heating has been observed to be 5 deg/sec or about half the rate of the slabs but with a positive feedback mechanism. So, even with a small total volume of BK7 compared to the slabs, its contribution to overall wavefront error will dominate. Results for various surfaces varied widely. Uncoated surfaces and to a greater extent, coated ones caused the majority of the absorption (up to 1 deg/sec for the poorer coatings) in low absorption (i.e., quartz and YAG) samples that were studied. Care must be taken to verify all coatings to have low absorption. This is best done with the laser in which they will be used. Surface contamination from dust caused significant (> lambda/2) wavefront

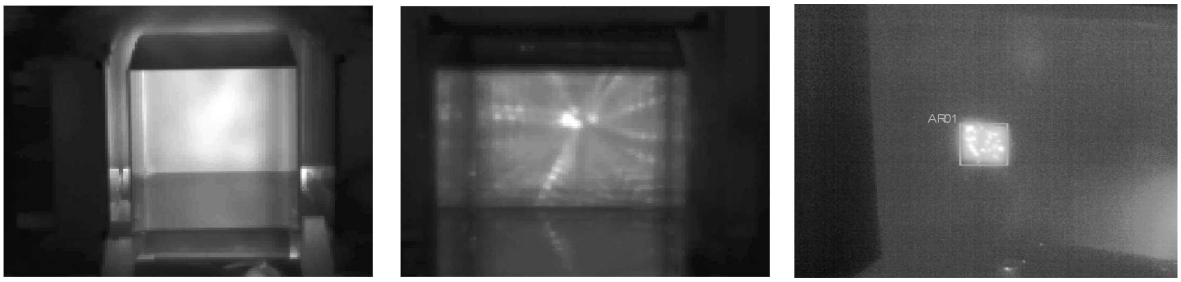

Figure 6. Thermal images used to characterize the origin of thermally-induced wavefront errors. (left) Observation along the optical axis of the resonator at near-normal incidence to the gain medium. The thermal profile induced by diode pump nonuniformities can be seen. (center) From a similar perspective, the themally-induced profile from mode-media interactions. In the cavity was a (slightly) absorbing material whose intended purpose was to inhibit convection cell growth adjacent to the gain media. Unfortunately, absorption at the lasing wavelength was slightly too high causing a positive feedback situation in which hot spots in the near-field profile induced self-focusing. (right) All optical components underwent careful examination under the intense, tightly-focused output of the LLNL DPSSL in a stable resonator configuration at approximately 6 kW/cm^2. This intensity is over twice the intensity to which the intracavity optics of a 100 kW laser of similar design would be subjected.

distortions at uncorrectable spatial frequencies. Thermal conductivities were not high enough to smear such features out to correctable spatial frequencies. Attempts were made to measure a temperature rise in air. Although expected to be low, considering the large volume of air within the cavity, it could add up to a significant contribution. Also, the sign of the temperature-induced index change is of the opposite sign as the slabs and would, therefore not induce self-focusing but rather thermal blooming. No temperature rise was detected, even though the laboratory environment was class 10,000. Environmental controls such as air filtration would further reduce any effect of atmospheric absorption. Note that absorption within a cavity is of much greater concern than absorption along the propagation path for two reasons. First, because the propagation is multi-pass in cavity vs. single pass in the atmosphere. This provides positive feedback for aberration growth. Second, most application that require propagation will, in practice involve slewing the laser beam and hence propagating through a different volume of air for each pulse.

Something to keep in mind when considering the mode-media interactions is diffusion. Diffusion of heat will limit the spatial frequency that needs to be corrected. Without it, diode imprint or localized hot spots from dust or coating imperfections would introduce large, uncorrectable, high-spatial-frequency errors. Materials with high thermal conductivity are best at limiting spatial frequencies to correctable range.

4. CURRENT SSHCL PERFORMANCE

The performance of the SSHCL at LLNL improved greatly within a six month period following an objective performance review process in the fall of 2005. Several engineering improvements, outlined above, made possible a greater than 40x improvement in total energy deliverable on target. Replacing all intracavity optics and coatings with low absorption counterparts (4x), increasing the number of degrees of freedom of the correction system (1.3x), homogenizing the pump irradiance profile (net 2x) and compensating for depolarizing effects (>4x). Currently, the laser can produce a 2 xDL, 10 kW, wavefront- and polarization-corrected beam for at least 5 seconds (see Figure 7). This power level is only an order of magnitude away from the near-term 100 kW goal. Swapping out gain media, as has been demonstrated, can enable unlimited run time with just 3 or four sets of off-line-cooled gain media.

Unfortunately, the full extent to which performance increased is not known. Not all of the improvement have been fully vetted. The off-loaded focus corrector has the potential to further increase run-time in the current pumping geometry by another factor of two by increasing the effective dynamic range of the control system. Initial experiments on the edge-pumped geometry indicate that it reduces pump inhomogeneity and the wavefront correction required dynamic range to a level that is acceptable at 100 kW and even beyond.

5. CONCLUSIONS

Solid state lasers provide a compelling path for high-brightness, directed-energy systems. Various approaches are currently being explored. The application space for such systems is still being vetted. It is too early to tell which approaches will

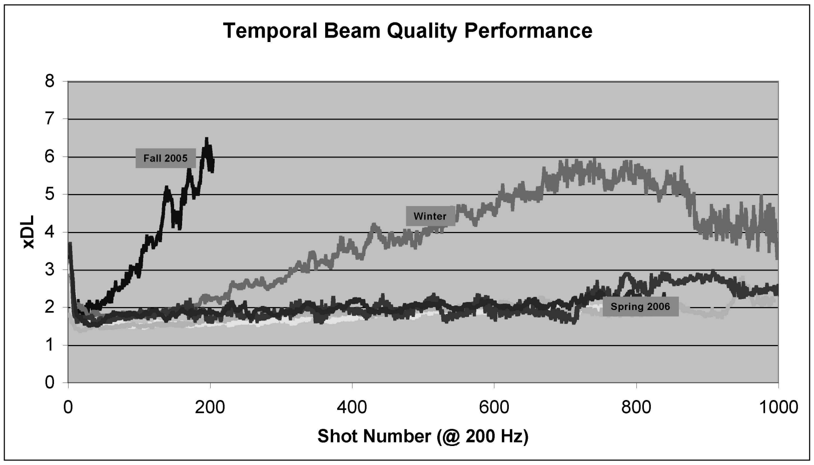

Figure 7. Laser performance increased dramatically over a 6 month period from an effective run time of barely a quarter of a second (50 shots) to a full 5 seconds (1000 shots). The performance was achieved through the use of a combination of engineering improvements relevant to any high power laser design.

work best for which applications. Virtually all of these approaches will need some sort of wavefront control. Much work is being done in improving wavefront quality and control schemes that will benefit any of these approaches. Recent advances on the SSHCL have increased not just run time, but total deliverable energy, by greater than a factor of 40 in less than 6 months. Although such a pace of performance increase is above average, it is reaffirmation that, with the proper allocation of resources, in a few years DPSSL technology could scale by another order of magnitude and achieve its 100 kW, near-term goal.

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