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LLNL-BOOK-433854

# Heat Capacity: Chapter 8.4

M. Rotter, R. Yamamoto

June 1, 2010

High Power Laser Handbook

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**System Architecture**

Over the past decade, scientists and engineers have actively engaged in the development of the key technologies required to realize the performance potential of the Heat Capacity Laser (HCL). Several scientific institutions around the world, most notably the Chinese Academy of Sciences in Beijing[1] and Shanghai[2] and the Lawrence Livermore National Laboratory (LLNL) in California[3], have been developers of this type of solid state laser architecture. The fundamental feature of the heat capacity laser that makes it unique from other solid state lasers is the distinct separation of the lasing action, from the cooling required of the laser gain media. Heat is stored in the laser gain media during the lasing process, then cooled off-line, away from the laser beam line. This allows aggressive cooling methods of the laser gain media to be realized, since the cooling does not interfere with, and is independent of the lasing process.

A second, and very important attribute of the heat capacity laser is the extremely simple design of the laser cavity, utilizing a single aperture architecture comprised of large laser gain media (slabs) pumped by arrays of high powered diode bars. Figure 1 shows the current configuration of the heat capacity laser used at LLNL[4].

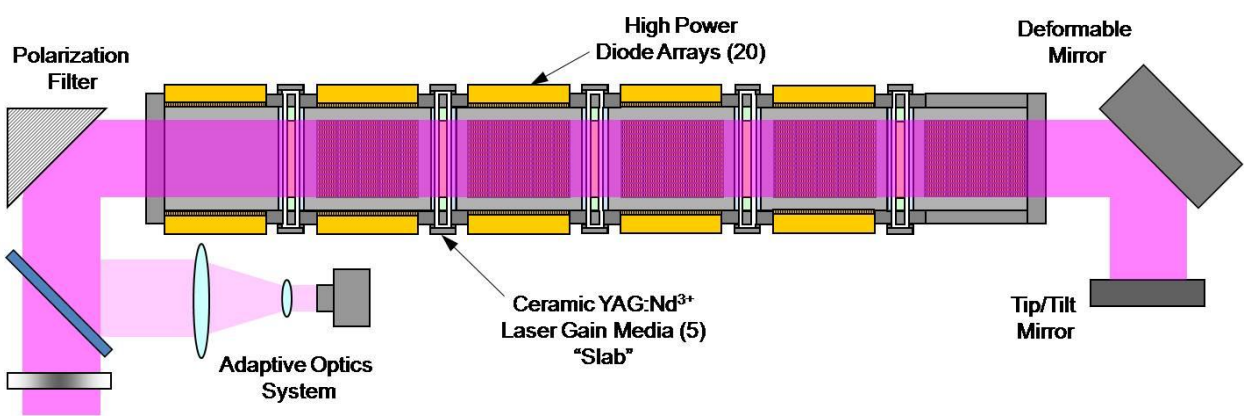


Figure 1: Heat capacity laser architecture in use at LLNL

The basic building block of the heat capacity laser is the laser gain module, which consists of a single slab pumped by four high powered diode arrays, two on either side of the slab. Each diode array pumps the slab's adjacent face at a defined angle, providing uniform pump light intensity across the entire slab face. In this particular example, the laser gain media used is a transparent ceramic YAG:$Nd^{3+}$ slab, edge-cladded with Cobalt/GGG (Gadolinium Gallium Garnet) to suppress amplified spontaneous emission. Shown in Figure 1 are five gain modules,

interlocked to form a compact cavity from which energy is extracted as a free running resonator. An intra-cavity adaptive optics (AO) system, consisting of a wave front sensor, deformable mirror, tip/tilt mirror and controller, maintains wavefront phase uniformity. The output laser beam wavelength for this heat capacity laser configuration is 1064 nanometers, and the diode light pump wavelength is 808 nanometers.

**Current State of the Art**

In January 2006, the heat capacity laser at LLNL achieved 67 kW of average output laser power for short fire durations, setting a world record for pulsed, diode-pumped solid state lasers, equating to 335 joules/pulse at a 200 Hz pulse repetition rate[4]. The pulsed heat capacity laser has a 500-microsecond pulse width and utilizes up to a 20% duty cycle from the high-powered diode arrays. This power level was accomplished by pumping five transparent ceramic YAG:$Nd^{3+}$ slabs (laser gain media) in series, each having an active lasing region of 10 cm by 10 cm by 2 cm in thickness. Figure 2 shows both an end view and side view photo of this heat capacity laser system.

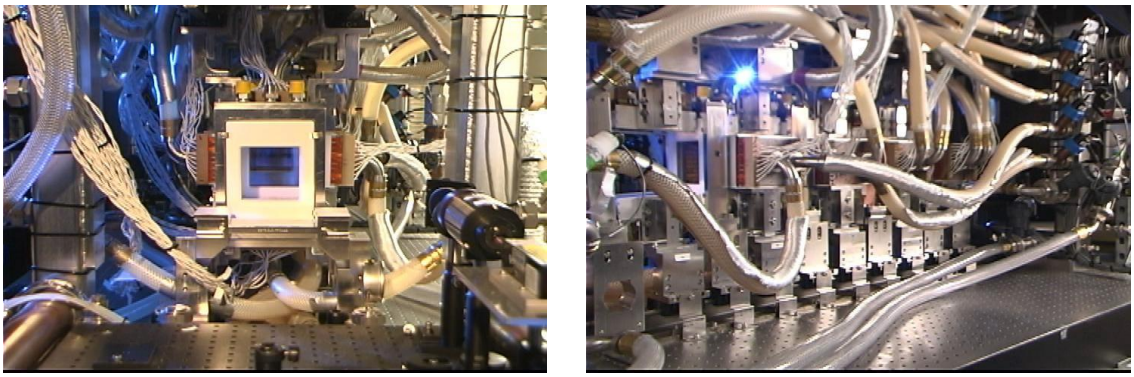

Figure 2: Current configuration of the heat capacity laser at Lawrence Livermore National Laboratory

Two critical hardware components make up the heat capacity laser. The first being the high powered diode arrays, which are used to pump the laser gain media. Each diode array is comprised of hundreds of relatively small, but very high-power diode bars, carefully aligned and precision assembled to form a homogeneous diode array. Figure 3 shows a state of the art high powered diode array manufactured by SiMMtec[5]. This diode array is comprised of 560 individual diode bars (7 rows of 8 ten-bar tiles per row), capable of producing 100 kW of peak power. Electrical to optical conversion efficiency for a diode array is approx. 40 to 50%, giving rise to a significant cooling requirement to dissipate the waste heat generated (a cooling water

flow rate of approx. 10 gallons/minute per diode array). In addition, the temperature of the cooling water must be maintained to within a few degrees, to ensure that the wavelength of light being emitted by the diode bars is centered on the optimum absorption wavelength of the laser gain media. As a frame of reference, each high powered diode array is about the size of a small loaf of bread, yet weighs about twice that of a standard bowling ball.

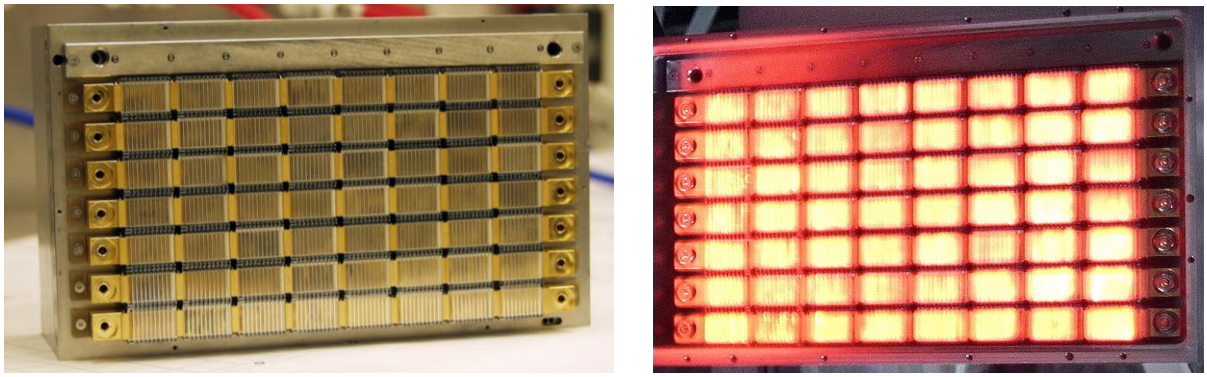

Figure 3**:** 100 kW, 560 bar, diode array manufactured by SiMMtec[5]

A detailed view of the structure of a ten bar tile is shown in Figure 4. It shows the relative relationship between all of the major components of a diode package, and the sophistication of the design. Many processing steps, from etching the coolant passages in the glass block to accurately positioning and soldering the actual diode bars to the etched silicon submount, are required to make this sophisticated device.

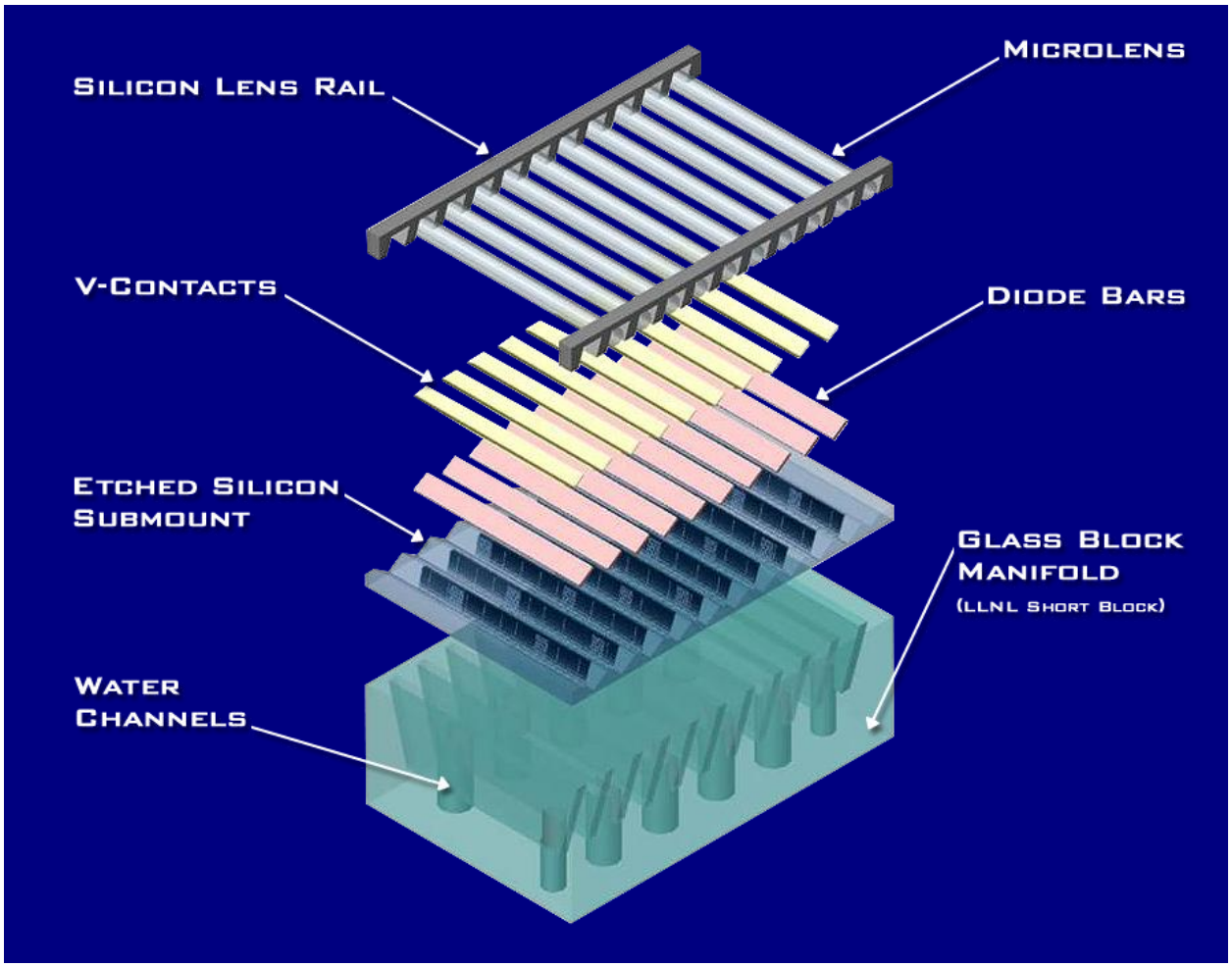


Figure 4: Ten bar tile architecture as manufactured by SiMMtec[5]

Figure 5 is a graph of output power vs. current into the diode bars for quasi continuous wave (CW) operation. Approximately 2 kW of peak output power is achieved at a drive current of 140 amps, with an electrical to optical efficiency of 55%. These ten bar tiles are 'burned-in" for a period of 12 continuous hours at 165 amps and 20% duty cycle, well in excess of the nominal operating parameters. This ensures the desired performance under safe and robust operation.

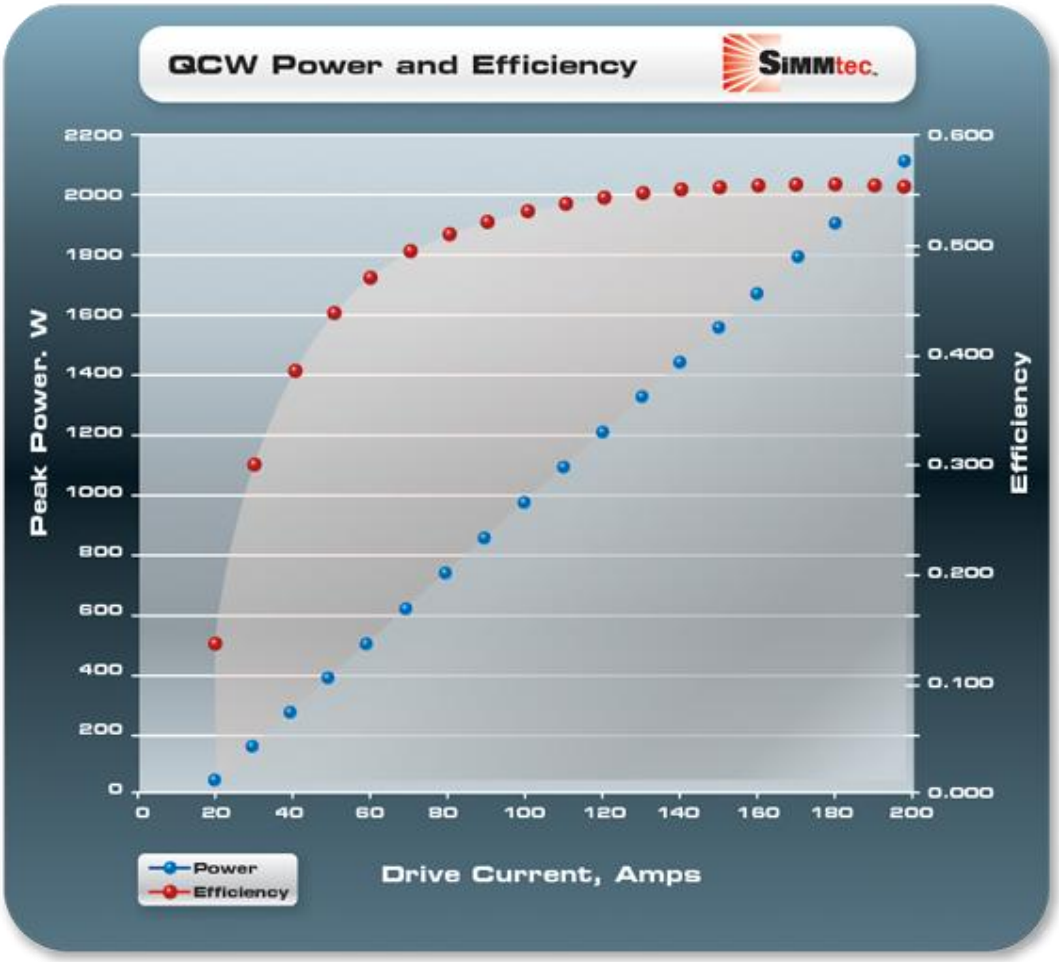


Figure 5: Ten bar tile performance as manufactured by SiMMtec[5]

The second critical hardware component is the laser gain media. The advent of large transparent ceramics as a laser gain media is a key technological advancement in the development of the heat capacity laser. This is primarily because the power of the heat capacity laser scales linearly with the size of the laser gain media; i.e., the larger the slab cross-sectional area, the more power that is produced by the laser. The ability for transparent ceramics to be made in very large sizes, on the order of tens of centimeters in size, contributes significantly to the practicality of the heat capacity laser architecture and its power scaling potential.

Transparent ceramics have several other advantages over traditional single crystal laser gain media in addition to being able to be made in very large sizes. Although forming a ceramic slab requires careful process control, it generally takes only several days to complete. Whereas, growing single crystals often requires weeks to months of continuous process time, with little guarantee that the crystal will not crack during the final cool down stage of fabrication. Ceramic slabs also have much higher fracture toughness than single crystals, and are much less likely to shatter or undergo catastrophic breakage when thermally shocked. Crack growth in transparent ceramics is inhibited by the numerous grain boundaries at the nano-particle size level, creating physical barriers and resistance to crack propagation. Transparent ceramics also exhibit little or no residual stress from the manufacturing process, creating a more optically desirable laser gain media. Higher dopant concentrations are possible, and doping is very uniform in transparent ceramics as compared to single crystals. During the growth of single crystal boules, the dopant ions tend to be refined out so that significant, unwanted doping gradients can occur.

Benefits of transparent ceramics versus single crystals for laser gain media include:

- Much larger sizes attainable – limited only by size of furnace hot zone.
- Complete fabrication in several days versus weeks growing single crystal boules.
- Different “near-net shapes” can be made to optimize performance parameters.
- Higher concentrations of optically active ions are possible.
- More uniform distribution of optically active ions.
- Low or no residual stress birefringence.
- Much higher fracture toughness and shatter resistance.
- More than one component (edge cladding) can be included in a single slab.
- Tailored distribution of optically active ion(s) is possible.

In Figure 6, the object on the left is a 10 by 10 by 2 centimeter transparent ceramic neodymium-doped yttrium aluminum garnet (Nd:YAG) laser gain media (slab) designed for use in the heat capacity laser at LLNL. The object shown to the right is a transparent ceramic Nd:YAG slab, integrally framed (edge cladded) with transparent ceramic samarium doped YAG (Sm:YAG), which is used to suppress amplified spontaneous emission (ASE). Both transparent ceramics were produced by Konoshima Chemical Company[6] and Baikowski Japan Co. Ltd[7].

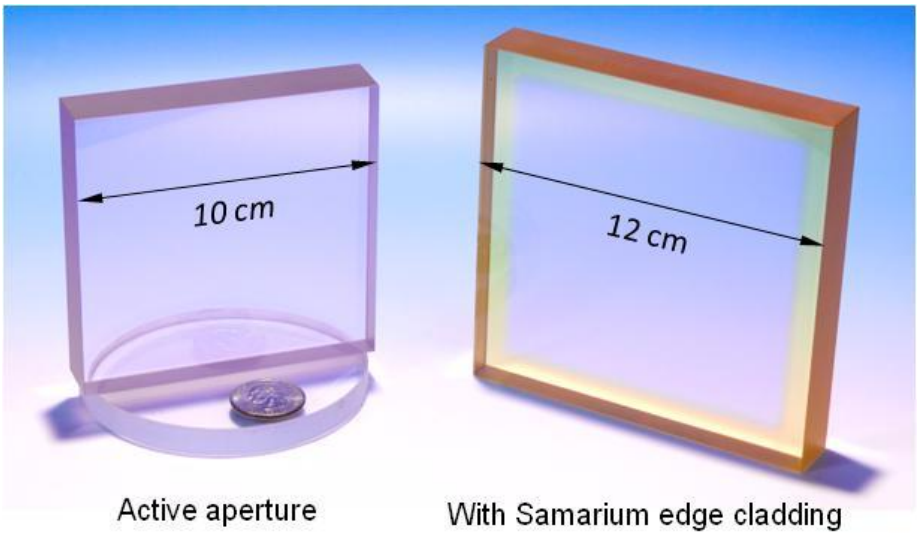


Figure 6: Transparent ceramic laser gain media manufactured by Konoshima Chemical Company and Baikowski Japan Company Ltd

The following photo is an end view of the heat capacity laser at LLNL, showing a 10 cm square transparent ceramic laser gain media being pumped by high average power diode arrays.

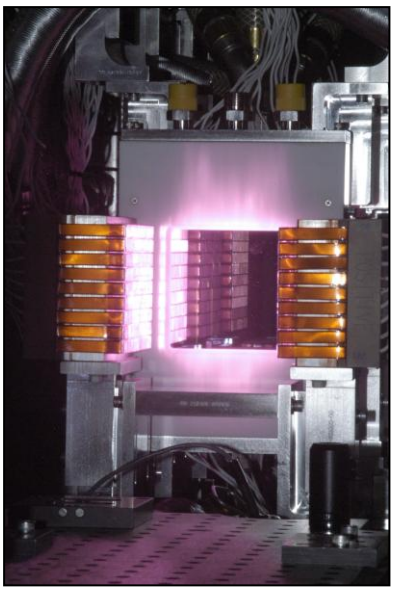

Figure 7: Energized diode arrays "pumping" a transparent ceramic laser gain media

In a typical heat capacity laser operation with the architecture as described above, at 25 kW average laser output power, 200 Hz pulse repetition rate and 10% duty cycle for the high powered diode arrays , the bulk temperature of a transparent ceramic laser gain media will increase from room temperature to approximately 130 degrees Celsius in about 10 seconds of

continuous lasing operation when working in its heat capacity mode of operation (no active cooling of the laser gain media during lasing). Although transparent ceramics have demonstrated no cracking or physical damage at temperatures of 200 deg C, standard engineering practice dictates a slab change-out after a 10 second run. This allows material stresses developed at this elevated slab temperature to remain well within reasonable values for reliable operation.

After lasing for 10 seconds, the transparent ceramic can either be cooled in-situ or moved off-line to be aggressively cooled. Several methods for slab cooling have been demonstrated with good success. As examples: cold plates are moved to within a few thousandths of an inch of the slab faces to literally suck the heat out of the slab, cold gas is flowed across each slab face, or a fine mist that absorbs the heat is applied to the slab face surface. The requisite cool down time to get the hot slabs from their elevated temperature down to room temperature can vary from tens of seconds to several minutes, depending on the type of cool down system used. The actual application of the laser and how it will be required to operate (duty cycle, etc.) will dictate the type of cooling system that is most suitable. The flexibility that the heat capacity laser has with regards to how it is cooled is another key attribute for using this type of laser architecture, particularly for use in real world applications.

**Scaling Approaches**

The heat capacity laser architecture described has confirmed that significant amounts of laser output power (67 kilowatts of average output power) can be produced in a very small volumetric footprint, via an extremely simple and straightforward laser cavity design. The 5 laser gain module heat capacity laser shown in Figure 2 will fit on a typical dining room table, as an example of just how compact the heat capacity laser actually is. Increasing power of the heat capacity laser scales linearly in each of these three independent ways:

- Adding more in-line laser gain media (slabs).
- Increasing the cross-sectional area (and corresponding increase in diode pump light) of the laser gain media.
- Increasing the duty cycle of the high powered diode arrays.

Increasing power of a heat capacity laser is somewhat analogous to increasing the power in a traditional automotive internal combustion engine. Adding more cylinders to an engine

(increasing from 4 cylinders to 8 cylinders as an example) is analogous to adding more laser gain media (slabs) to the laser; increasing the bore size of the piston (the piston diameter) is analogous to increasing the cross-sectional area of the laser gain media (slab); and increasing engine speed (RPM's: revolutions per minute) is analogous to increasing the duty cycle of the high powered diode arrays (from a laser pulse format of 10% duty cycle to "CW", continuous wave operation). The simplicity of increasing any or all of these three parameters makes for a very straightforward and practical approach to increasing the output power of the heat capacity laser.

Looking ahead to the next plateau of power, a concept design for a megawatt class heat capacity laser is as follows:

- 16 transparent ceramic Nd:YAG laser gain media (20 cm x 20 cm x 4 cm thick) arranged in series.
- 64 high powered diode arrays at 84 kW of average output power per array.
- High powered diode array duty cycle of 20%.

The above parameters follow the general power scalability formula for a heat capacity laser: increasing the number of laser gain media, increasing the size of the laser gain media and increasing the duty cycle of the high powered diode arrays. Although many details of the entire laser system architecture remain to be resolved, there is no fundamental reason why the heat capacity laser cannot attain megawatt class output power utilizing the same nominal architecture that is currently used today. In addition, the only technology that has not been physically demonstrated to-date is the 20 cm size transparent ceramic laser gain media. Thus, the "leap" to significantly higher laser output power levels is more of an evolutionary engineering process, rather than waiting for a serious technological breakthrough (or miracle) to occur.

**Experimental Results & Applications**

Because of its large output power capability, and simple architecture - corresponding to ease of operation and compact footprint, the heat capacity laser is often used to conduct a variety of laser-material interaction experiments. Several investigations using the heat capacity laser at

Lawrence Livermore National Laboratory[8] are cited to provide examples of the type of capabilities the heat capacity laser has.

I. Rapid material removal (boring/ablation):

Experiments were conducted showing laser interaction on steel targets, initially in a static configuration. The collected data is oft times represented by the term Q* (Q Star), the amount of energy required to remove 1 gram of material. In this particular experiment, a 25 kW laser (produced by the heat capacity laser, having a laser spot size of approximately 2.5 cm square, and a pulse frequency of 200 Hz) impinges on a 1 inch thick block of carbon steel. The results of the laser-target interaction after 10 seconds of continuous laser operation are shown in Figure 6. The initial hole through the steel block was generated after just 6 seconds of run time.

Figure 8: 25 kW on a 1" thick carbon steel target for 10 seconds

It can be seen that a significant amount of material was removed during this laser-target interaction. This type of experimental data can be useful in determining machining rates for laser cutting tools, as well as in estimating burn through times for targets of military interest.

II. Aerodynamic imbalance due to air flow interaction:

The following five photo sequence (Figure 9) shows an experimental simulation of a laser beam interacting with a thin aluminum structure in flight. The laser beam heats the material surface (13 cm by 13 cm spot size), softening it to the point where initiation of a crack and the ultimate rupture of the material occurs. A high rate of air flow is directed across the surface to simulate flying through the atmosphere. This experiment demonstrates that well before melting of the aluminum sheet, the material softens and then bulges outward due to the low-pressure region formed by the flowing air. The hydrodynamic force generated by the stream of flowing

air is sufficient to rip away the aluminum skin. The thin skin is ripped off due to the force of the air flow over the softened skin, promoting aerodynamic imbalance, either destroying the structural integrity of the target, or sending it off its desired flight path.

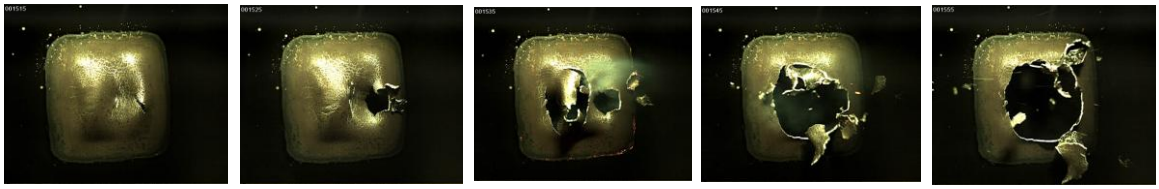

Figure 9: Laser interaction of a thin-walled aluminum sheet with air-flow; 0.07 seconds total elapsed time

III. Laser used for humanitarian mine clearing:

In 2004, the Lawrence Livermore National Laboratory[9] won a Research & Development 100 award for development of a heat capacity laser for use in humanitarian mine clearing. Experiments showed that due to the pulsed format of the laser system, the laser beam could bore through soil at a very fast rate, heat up a buried landmine in seconds, and raise the temperature of the high explosive within the landmine sufficiently for deflagration to occur.

The physics of the digging phenomenon is quite simple. Because of the heat capacity laser's pulse format, the peak power generated in each laser pulse is many times that of the average power of the laser. This high peak power per pulse corresponds to a high peak temperature intensity in the soil substrate. All soils contain some residual amount of moisture, no matter how dry and void of moisture they seem to be. The high peak power pulses of laser light generated by the heat capacity laser impinge on the soil in a very focused area, and actually vaporize the moisture in the soil. This vaporization creates a micro-explosion of the moisture on a pulse-by-pulse basis. It is this micro-explosion that generates the force required to displace the soil, allowing the laser to penetrate to the intended target. Each laser pulse vaporizes more moisture, thus creating more explosions, which allows the laser to penetrate deeper and deeper into the soil. Once the laser hits the outer casing of the landmine, it rapidly begins to heat the material. Within a few seconds, the temperature of the high explosive in the landmine is significantly raised (a few hundred degrees Celsius) to initiate deflagration.

Figure 10 provides a concept overview of the heat capacity laser system used for humanitarian mine clearing. The system can be used for both buried and surface landmines, and can be operated at significant standoff distances to reduce the amount of human exposure within

the blast affected zone. In addition, the power of the heat capacity laser can be easily modulated such that the high explosive material in the landmine does not explode, but simply “sizzles” in place, thus further reducing the risk of human exposure to material fragmentation and the resulting shrapnel.

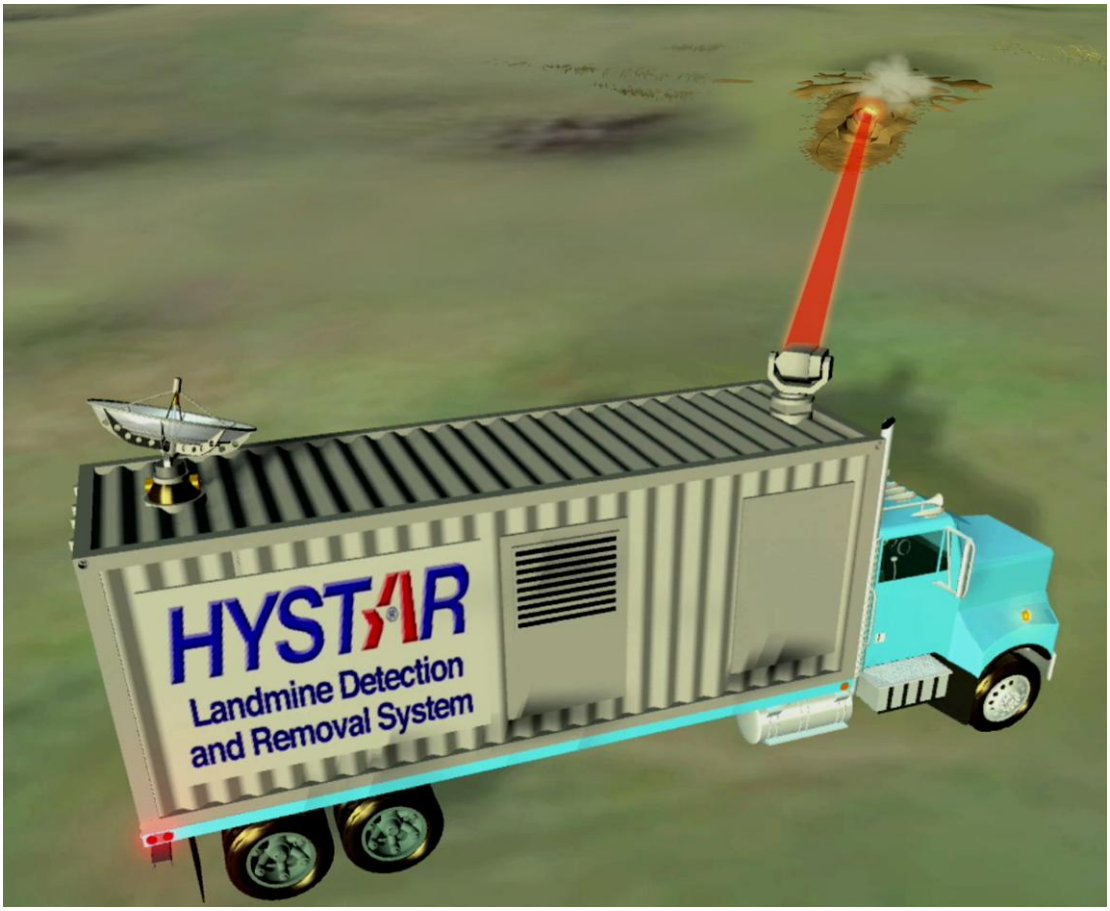


Figure 10: Concept of the heat capacity laser system used for humanitarian mine clearing

IV. Self-contained 400 kW heat capacity laser on a military vehicle:

It is obvious that the heat capacity laser’s many attributes will lend itself to military applications. The heat capacity laser, as described above, can be scaled to very high powers, while still maintaining a very low weight and compact footprint. In addition, due to its simple laser architecture, it is extremely compatible with military requirements for being robust, reliable and easy to maintain. Figure 11 shows an artist's conception of a 400 kW heat capacity laser system on a mine resistant ambush protected (MRAP) vehicle. The system as designed is fully

self-contained, including the laser, power management system, thermal management system, beam director and computer control system. Initial targets could include rockets, artillery and mortars (RAM) as well as improvised explosive devices (IED's).

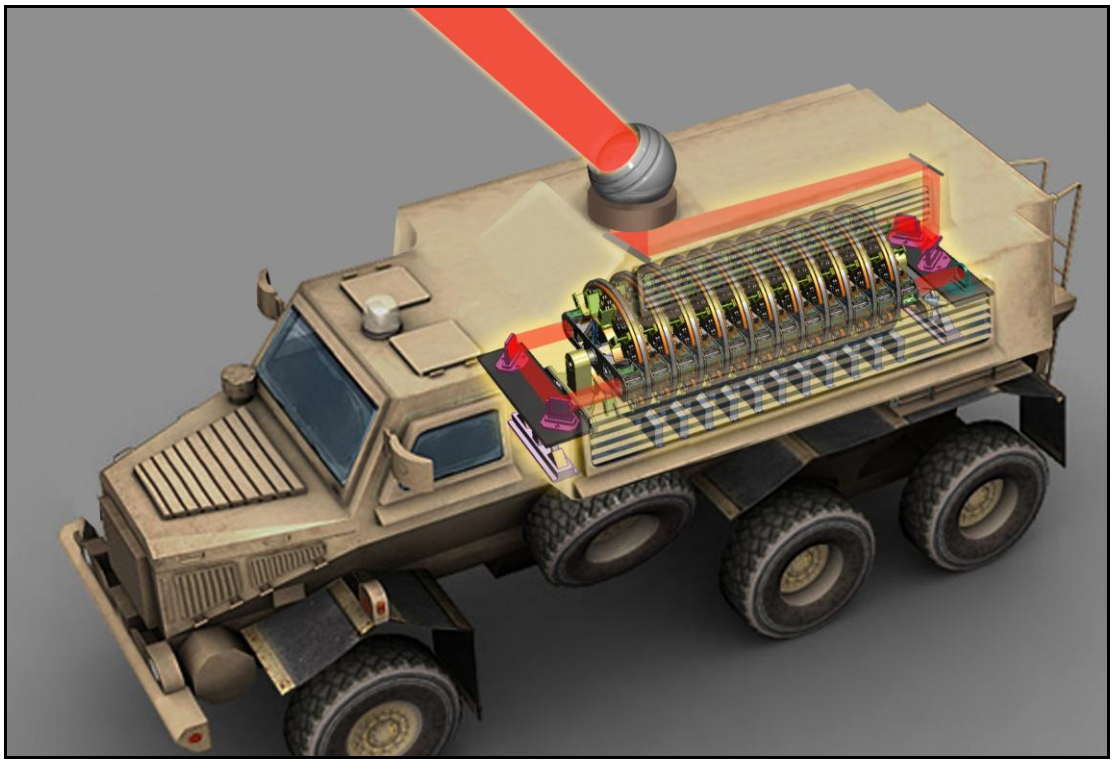

Figure 11: 400 kW heat capacity laser system on a mine resistant ambush protected (MRAP) vehicle

**Summary**

The simple architecture of the heat capacity laser, including the separation of the lasing action from the cooling of the laser gain media, has demonstrated that it is a laser that can be used for practical applications. Key components, such as the high powered diode arrays and the transparent ceramic laser gain media, are available from industry, providing additional support for the maturity and practicality of the laser design. Experimental results using the heat capacity laser show conclusively not only its power scalability, but also demonstrate the many uses for the laser system. The near future of the heat capacity laser will see it transformed from a laboratory device, to a bonafide product geared for a variety of real world applications and providing solutions the world over.

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Prepared by LLNL under Contract DE-AC52-07NA27344.