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Toward High Brightness, Multi-Kilowatt Solid State Lasers

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Abstract

HIGH average power (HAP) solid state laser output with improved beam quality has introduced new capabilities in materials processing. At the 500 watt level and with a beam quality of a "few" times the diffraction limit, the General Electric Nd:YAG slab is able to drill 5 cm of stainless steel in a few seconds. We expect that 2-3 kW of near infrared laser output in a low order spatial mode would enable metal working now unknown to industry. The HAP output of slab lasers is limited by the size of the available laser crystals and the pump power. Core free, six cm diameter Nd:YAG boules have been grown by Allied Signal Corp. on an experimental basis. High optical quality Nd:GGG can be obtained up to 10 cm in diameter. We present the results of our modeling based on these crystals pumped by advanced arc-lamps or laser diode arrays. We project HAP laser outputs of 1.6 kW from an existing (but un-tested) Vortek pumped $18 \times 7 \times 0.5$ cm^3 Nd:GGG oscillator and about 2 kW from a $20 \times 4 \times .7$ cm^3 diode pumped Nd:YAG device. Several kW of laser output can be expected from two such slabs in a MOPA configuration before optical damage limits are reached. The three dimensional stress-optic code (TECATE) which we used to optimize our designs, was normalized to available experimental data obtained with the above Nd:GGG slab at the 500 Watt level and a 40 Watt diode pumped Nd:YAG test bed. Our calculations indicate the essential parameters for attainment of high beam quality. Cooling uniformity across the pumped faces of the slab is critical and the location of the transition between pumped and un-pumped regions towards the slab tips is very important. A flat pumping profile was found to be desirable and predicted one wave of distortion which should be correctable over about 75% of the aperture however, an even better wavefront was predicted over 90% of the aperture when the regions near the edges of the slab were slightly over-pumped relative to the central regions and the regions near to the ends were tapered to compensate for transition effects. The challenge is now to design reflectors and diode pumping arrays to provide the desired pumping flux profile on the face of the slab with less than 1% uncertainty. Our spectral measurements of the Vortek^{TM} lamp show this lamp to be a superior HAP pumping source for slab laser designs above one kW. Our lamps have been optimized for efficient pumping by pulsing them at the best current density. As production costs come down, however, laser diodes will gradually replace lamps in high brightness solid state lasers for industrial materials processing.

1.0 Introduction

SUBSTANTIAL experience with solid-state laser machining of metals, plastics and ceramics has been accumulated in recent years. Excellent accounts of this emerging technology are generating industrial interest as it becomes clear how economically superior near infra-red laser sources wedded to fiber optical distribution systems can be compared to e-beam or CO_2 laser welders.[1] Solid-state lasers have been used successfully in the automobile industry for almost two decades.[2] For example, Nd:YAG lasers

[1] G. McFadden and D. M. Filgas, *Designing Nd:YAG Lasers for Higher Powers*, Lasers & Optronics, Vol. 9, No. 8, p. 32, August 1990

[2] D. M. Roessler, *U.S. Automotive Applications of Laser Processing*, The Industrial Laser Annual Handbook, 1988 Edition, edited by D. Belforte and M. Levitt, Penwell Books, Tulsa, Oklahoma, 1988

having output power levels of only 350 W drill holes angled at 35 degrees in hardenable steel (R_c60 hot forged powder metal alloy) transmission components such as gears. These holes are 7.5 mm deep by 1.5 mm in diameter and --- cut in 3.5 seconds with the medium power lasers now commonly available without the assistance of an oxidizing gas. A more recent account of the potential of laser materials processing in the automobile industry with many more examples and 146 references has been prepared by General Motors Research Laboratories.[3]

With the advent of face pumped zig-zag slab lasers, greatly improved beam quality has dramatically extended the drilling performance of Nd:YAG lasers. General Electric Aircraft Engines is committed to the use of Nd:YAG lasers in turbine engine manufacture, and thus actively supports internal research and development of these systems. The CF series (wide-body) engines use 80,000 laser drilled transpiration cooling holes while the smaller CFM series (commuter) engines have about 40,000 cooling holes. GE engineers are increasing the numbers and depths of these holes in superalloy steels while calling for similar holes in ceramics and composites in their new engine designs. Early this year GE announced 1000 W performance from their face pumped lasers in several popular magazines.[4] Dramatic examples of face-pumped laser performance attributable to their high power, superior beam quality and fiber optic compatibility have been reported:[5]

- Holes drilled at oblique angles with single laser pulses "on the fly" in 1.5 mm thick steel sheet at the rate of five per second.
- Five cm deep holes less than 1 mm in diameter drilled in stainless steel.
- A single 0.5 mm fiber, 50 m in length is 90% efficient in transmitting 40 J / 2 ms laser pulses at 900 W average power.

GE's research group is not the only one to have recognized the potential of face-pumped lasers. The promise of virtually unlimited clean energy from controlled fusion has motivated research into Inertial Confinement Fusion (or Laser Fusion) at LLNL for almost 20 years. In this time seven generations of Nd:Glass lasers for fusion experiments have been built at LLNL. The latest of these, NOVA, is the world's most powerful laser capable of delivering up to 100 kJ in 1 ns (or 100 TW) to laser fusion target assemblies. While laboratory researchers were scaling fusion yields up at LLNL, companion efforts involving both LLNL and LANL scientists scaled nuclear device driven fusion capsules down at the Nevada Test Site. Experiments conducted by this means have allowed demonstration of excellent performance, putting to rest fundamental questions about basic feasibility to achieve high gain. As now envisioned, an ICF electric power plant will need a driver delivering 3 to 5 MJ per 5 to 7 ns pulse at 10 Hz. LLNL has maintained an ICF laser driver research effort throughout its ICF program history and during the past several years face pumped solid-state lasers have become serious contenders for practical ICF drivers. With laser system simulators developed to a high degree at LLNL and a staff with a successful high power laser track record, several DoD agencies approached LLNL for assistance. Zig-zag slab laser development has been supported by DARPA and SDIO at LLNL for over four years. During the past two years, diode pumping technology for these devices has made rapid progress under both DoD and LLNL internal sponsorship. Thermo-optical design codes, optical propagation codes, laser materials development, laser pump source development and integrated tests of laser hardware at LLNL generally meet or exceed the standards of performance of corresponding technologies anywhere in the world.

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[3] D. M. Roessler, *Update on Laser Processing in the Automotive Industry*, GMR-6893 issued 12/12/89

[4] J. Keller interview with M. McLaughlin of GE, *GE Squeezes 1,000-W Beam From Face-Pumped Laser*, Military & Aerospace Electronics, Vol. 1, No. 4 April 1990

[5] J. P. Chernock, GE Research Ctr. Schenectady, NY, 1990

2.0 Material Processing Laser Requirements

IN their 1988 review of laser surface treatment, A. Bloyce and T. Bell give examples of many of the emerging laser surface engineering processes which are beginning to have a strong impact on manufacturing.[6] Fig. 1, adapted from their paper, indicates the laser irradiance and pulse duration regimes required for these processes. We have added drilling, cutting and welding of mild steel to the figure as well as a lower irradiance application, laser assisted hydraulic mining. Such laser material processing applications represent the largest segment of the laser system market. In 1989 alone, laser material processing system sales reached ≈$1.2B. Unfortunately for US competitiveness in the manufacturing arena, the USA has steadily lost market share since the invention of the laser. In 1989 about 43% of this market was Japanese, another 26 % European and the remainder, 31%, was USA supplied.

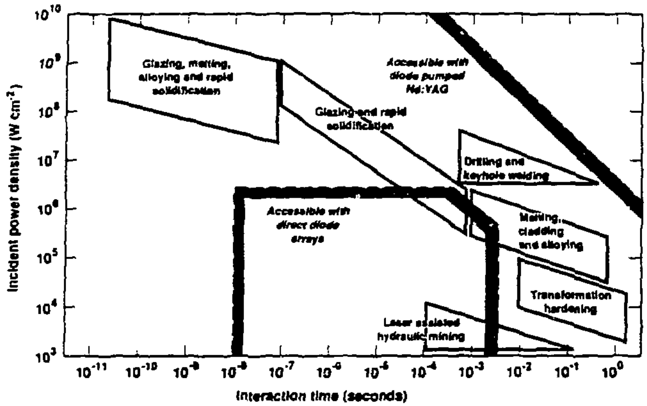

Fig. 1 Optical fiber delivered multi-kW solid-state lasers can access the treatment regimes of interest for laser material processing.

Beyond the sort of generic requirements suggested by Fig. 1, maufacturers around the globe are beginning to identify more specific requirements which, to one extent or another are already being met by lasers, but which could be accomplished more cost effectively by a diode array or a diode array pumped high radiance device. Several such requirements sets are outlined below. In addition to being optical fiber compatible and requiring kilowatt power levels, each application has its own unique specifications:

Punching cooling holes in aircraft engine turbine parts

- ≥ 30J per pulse
- 1 to a few msec pulse duration, may be bursts
- High radiance desired
- 5 to 30 Hz, "cut on the fly"

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[6] A. Bloyce and T. Bell, *Laser Surface Engineering*, The Industrial Laser Annual Handbook, 1988 Edition, Edited by David Belforte and Morris Levitt, PennWell Books, Laser Focus, Tulsa, Oklahoma (1988)

Welding mild sheet steel

- 1 to a few mm thick stainless steel
- $\geq$ 10 cm/sec welding and $\geq$ 20 cm/sec cutting
- Stand-off distances of tens of cm
- Beam quality $\approx 10\times$ diffraction limited
- Estimated power requirements: 2 to 4 kW

Machining composites and ceramics for aircraft

- Al:Carbon composites probably require ablative pulses
- Ceramics may require 2ω or 3ω short pulses
- Pulse shape and format flexibility needed

Laser Assisted Hydraulic Drilling

- $\geq$ 1kW/cm^2 must be delivered to the mining face.
- Laser beam must traverse $\approx$ 1 cm of water
- Off-road vehicle mounted for field mobility

ICF Driver Laser for Commercial Power

- 3 to 5 MJ/pulse at 10 Hz
- Laser diode's demonstrated electrical efficiency must be maintained as production is fully automated and scaled up
- Laser diode pump cost must be reduced to pennies/peak Watt

The final entry on this list outlines a solid-state ICF driver laser which becomes cost competitive with alternative power generation technologies *only* if volume production of laser diodes of order 10^9 peak Watts per year can reduce the price of laser diode pump arrays. Laser material processing could make up a large part of this.

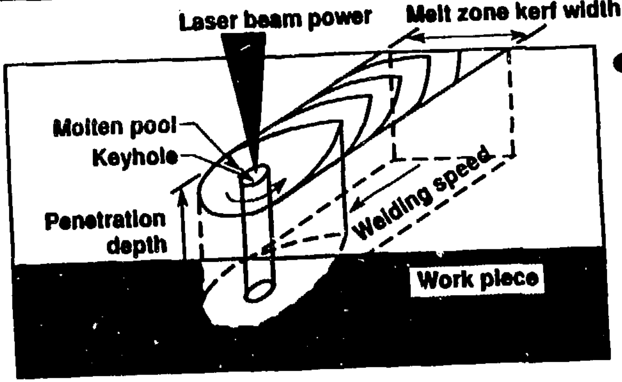
3.0 Calculated Laser Requirements for Sheet Metal Cutting and Welding

To weld sheet metal, a hot plasma line source (keyhole) should be established in the workpiece by drilling almost through the material at high temperature ($\approx 20,000°$ Kelvin) with a focused laser beam. Drilling proceeds after an initial few hundred nanosecond transient period during which the plasma is formed and the reflectivity of even polished metal surfaces becomes very low.[7] As the laser beam moves relative to the workpiece, molten metal flows around keyhole and resolidifies to form the weld. The plasma formation and drilling process is most efficient over a narrow range of irradiance, 5 to 50 MW/cm^2.[8] Care must be taken to avoid the formation of unwanted oxides and the strength of the uncontrolled melt region may be lower than that of the rest of the material. Cutting is a similar process except that molten metal is typically blown out of the kerf by an assist gas (Fig. 2). We have scaled the recently reported welding performance of three different Nd:YAG industrial laser systems to arrive at an estimate for the laser power and beam quality required of a fiber compatible solid state laser to match the demonstrated performance of the RS850 CO_2 laser system. At IMTS'90 we were told that

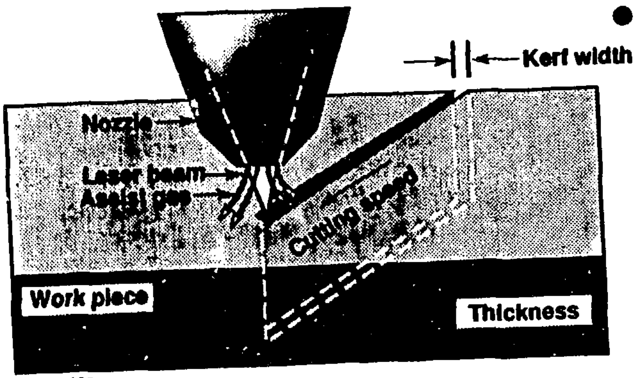
[7] M. von Allmen et al., *Absorption Phenomena in Metal Drilling with Nd-Lasers*, JQE, **QE-14**, No. 2, Feb. 1978

[8] M. von Allmen, *Laser Drilling Velocity In Metals* J. Appl. Phys., **47**, No. 12, Dec. 1976

Cutting and welding are similar processes



- Laser welding
  - — Energy is coupled into a plasma "keyhole" at high temperature (~20,000° K)
  - — As the workpiece moves, molten metal flows around the keyhole and resolidifies



- Laser cutting
  - — Energy coupling is similar to welding
  - — An assist gas is used to blow molten metal out of the kerf
  - — A reactive gas (O_2) can improve cutting speed

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Figure 2

this laser had been able to lap weld two 1 mm thick plates of steel together with a 1 mm bead width at almost 200 inches per minute. What follows are notional lasers which should be able to meet this goal based on our calculations and laboratory experience.

It is desirable to stay about 20 cm away from the work surface, presumably using a 20 cm focal length optic. Since practical focusing systems that can be conveniently carried by robotic arms can accommodate two centimeter diameter focusing optics with ease, we have selected one cm as our baseline beam diameter at the focus lens. There is a simple relation between the size of a partially coherent laser's focal spot and the size of a coherent patch or *speckle* on the focusing lens. If we arrange that the beam entering the final focusing lens is collimated; i.e., has an average radius of curvature of ∞, then the intensity spot 1/e radius on the workpiece will be

$$W_0 = \frac{2f}{kL_A} = .01 \text{ cm},$$

where $f = 20$ cm, $k = \frac{2\pi}{\lambda}$ and the lateral coherence length or speckle radius in the lens plane, L_A, is .07 cm. Many welding laser manufacturers report their laser's radiance in terms of the number of mm-mrad achieved at a given output power. The full angle subtended by a partially coherent beam which meets our specifications would be

$$\theta(L_A) = \frac{2}{\pi}\frac{\lambda}{L_A} = 1 \text{ mrad}.$$

If we require our beam to be about one cm across at the lens, then we need a beam quality of about 10 mm-mrad and more than a factor of two increase in this number would probably *not* be tolerable.

Martek Lasers Inc. provide data on their MM1800 three rod laser.[9] This laser delivers low powers in a beam 5 mm in diameter that diverges into an angle of 15 mrad; i.e., a 75 mm-mrad beam, and 1800 W into a beam about 2.5 mm in diameter that diverges into an angle of about 25 mrad; i.e., a 63 mm-mrad . Lumonics Inc. report that their model JK706 rated at 1000 W produces a 10 mm diameter beam that diverges into 10 mrad for a 100 mm-mrad beam.[9] Both of these manufacturers use a rod technology that does not scale favorably to higher radiance. It is unlikely, therefore, that a rod system can satisfy our requirements.

Zig-zag slab lasers achieve significantly better beam quality. The first commercially available laser of this type is the Munich Laser Systems model P500. This device produces a 6 mm $\times$ 6 mm square beam that diverges into 5 mrad for a 30 mm-mrad laser.[10] GE researchers have reported ≤ 10 mm-mrad beams at 1020 W and LLNL experience has been similar.[5] We conclude that our beam quality requirements can best be met by a face pumped slab Nd:YAG laser.

In the absence of a truly comprehensive theoretical treatment of keyhole welding, the most reliable way to estimate the power required is to scale from recent performance data accumulated with high power Nd:YAG industrial lasers. The Martek MM1800 rod laser has been used to weld monel at 20 in/min with a weld depth of 5.3 mm and a kerf width of about 3 mm.[1] From their quoted divergence and because their tests were conducted with f/5 optics, we can estimate their spot $1/e^2$ intensity radius as 150 to 200 μm. To meet our assumed requirements, we want about half this spot radius using an f/20 focusing system and we mean to get it by exploiting the much higher radiance of a slab laser. To scale the Martek data 5.3 mm to 2.0 mm depth, we can safely assume that the speed can increase by this ratio. We expect that the MM1800 could weld 2 mm thick sheet steel at 53 inches per minute or 2.24 cm/sec. It would not be able to do so using f/20 optics, however. The laser which meets our requirements will

[9] Lasers & Optronics 1990 Buyer's Guide, 8, No. 13, p. 292

[10] *Commercial slab laser cuts better than conventional YAGs*, Laser Focus World, 26, No. 8 August, 1990

interact with less material since its focal spot is half as large. We get another speed multiplier because of the smaller kerf, and we might choose to use the elliptical focus normally produced by slab lasers to avoid overlap problems at high speeds. A three-fold increase in speed owing to the smaller kerf is expected; so with 1800 W we should be able to weld two 1 mm sheets of mild steel together at a speed of 159 inches per minute or 6.73 cm/sec. The CO_2 laser manages 200 inches per minute so to match it we arrive at a required solid state laser power of:

$$P_L = 1800\frac{200}{\frac{5.3}{2}\frac{3}{1}20} \simeq 2300 \quad \text{Watts.}$$

A second *estimate* comes from scaling cutting data made with 2 mm thick galvanized iron sheet using the MLS P500 slab laser operated at 300 Watts. This laser was able to cut this particular material at 800 mm/min or 1.33 cm/sec. Unfortunately, no information is given on kerf widths, however, scaling to the required rate of 8.5 cm/sec would require

$$P_L = 300\frac{8.5}{1.33} = 1900 \quad \text{Watts.}$$

A final estimate may be made using data taken with the Lumonics JK706 oscillator-amplifier laser. This device has a beam quality lower than the rest, 100 mm-mrad. When used to weld Type 304 stainless steel to depths between 1.5 and 2.0 mm, this laser achieved a speed of 60 to 80 cm/min at a kerf width of 2.5 mm. Scaling the width down to 1 mm sets a range of laser powers required

$$2500 \leq P_L \leq 3400 \quad \text{Watts.}$$

This last estimate is the highest since it is based on data taken with the poorest beam quality laser. Lumonics notes that their laser welds are typically conduction loss dominated. The JK706 is the only model they produce delivering enough power density to the workpiece to do keyhole welding. We attribute this to relatively poor beam quality and Lumonics must agree since they now produce the JK707. The JK707 is identical to the JK706 except for a patented low divergence resonator that improves beam quality to about 20 mm-mrad, but lowers output power to 600 Watts. This system has cut 2 mm thick Type 304 stainless at 2.5 cm/sec with kerf widths between 0.5 and 1.5 mm. Scaling this data to the required speed,

$$P_L = 600\frac{8.5}{2.5} = 2040 \quad \text{Watts.}$$

Note that the extrapolation of the JK707 20 mm-mrad laser data is close to the P500 30 mm-mrad laser based estimate. The laser power required to meet our requirements is therefore taken *to be in the range* of 1900 to 2300 Watts.

The solid angle subtended by the our beam will have to be

$$\Omega = \frac{1}{\pi}\left(\frac{\lambda}{L_A}\right)^2 = 7.3 \times 10^{-7} \quad sr,$$

which would make the average radiance of a *2000* Watt laser with an 0.5 cm radius spot at the focusing lens

$$\mathcal{R} = \frac{2000}{\pi .5^2 \Omega} = 3.2 \times 10^9 \quad \frac{W}{cm^2 sr}.$$

We can assess the difficulty of our task by comparing this value of radiance to the theoretical maximum.

$$\mathcal{R}_{max} = 4\frac{2000}{\lambda^2} = 7.1 \times 10^{11} \ \frac{W}{cm^2 sr}$$

and to the values achieved by the industrial lasers mentioned above.

Table 1 HAP solid state lasers ranked by radiance

Laser (source)	Average Power Watts	Beam Quality mm-mrad	Radiance $MW/cm^2/sr$
NEC (5 rods)	2000	224	6.5
M34 *CGI*	250	74	7.4
NEC (3 rods)	800	120	9.0
JK-706 Lumonics	1000	100	16.2
Ω Adv. Rod CGI	250	35	33.1
P-500 MLS	500	*30 to 50*	50.0
MM 1800 Martek	1800	63	73.5
JK-707 Lumonics	600	20	243.2
Laboratory models which are not commercially available,			
GE FPL GE CRD	500	5	3242.0
Vortek-YAG LLNL	2000	10	3242.0
MPSSL LLNL	300	3	5404.0

At 5000 Watts, the RS850 CO_2 laser can achieve the requirement so long as its beam quality is held within 2.4 × the diffraction limit. The Martek MM1800 is a 70 × diffraction limited laser that reaches an average radiance of $\mathcal{R} = 5.2 \times 10^7$ which is about 61 times smaller than required. The MLS P500 delivers a radiance of $\mathcal{R} = 7 \times 10^7$, about 45 times too low. The JK706 reaches a radiance of only

$\mathcal{R} = 1.6 \times 10^7$, about 200 times too low, while the JK707 comes closest to the mark with $\mathcal{R} \approx 2.8 \times 10^8$, still about 12 times too low. What we require is a face pumped slab laser with a beam quality of about 10 times the diffraction limit or better that is capable of delivering 1900 to 2300 Watts. Fig. 3 shows an LLNL simulation that contends that these parameters can be met by a single *LLNL crystal laser* using Nd:YAG. Table 1 lists commercially available lasers, ranked according to radiance, along with two LLNL designs which as of this writing are just beginning to be tested.

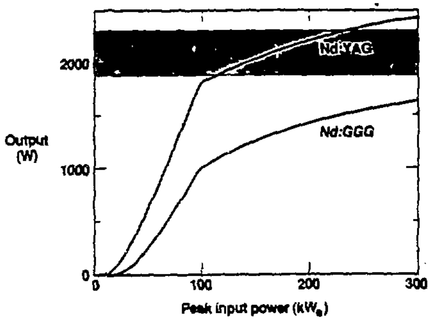

Fig. 3 Calculated performance of LLNL Nd:GGG and Nd:YAG slab lasers

LLNL has performed interferometric measurements of a Nd:GGG slab. This slab pumped by Vortek arc lamps achieved 490 W beams with smooth near-field profiles in early tests. We have completed initial resonator calculations *that include these measured aberrations* and an example can be found in Fig. 4. The calculated far-field beam profile *shown* in Fig. 4 exceeds our welding radiance requirement by a factor of more than four.

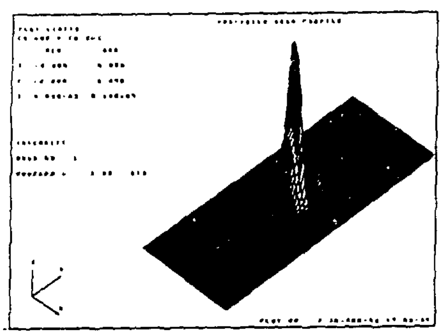

Fig. 4 Far-Field beam profile calculated for LLNL Nd:GGG slab laser.

Since radiance is a conserved quantity in an ideal passive optics system, even a fiber delivered slab laser beam *may* retain its high brightness with good design, but a poor quality input beam can never be made *more* coherent by fiber transport *alone*. *Fig. 5 is a plot of kerf width versus speed for 2 mm thick* steel that shows the performance of each laser mentioned. The MM1800 comes closest to meeting our speed requirement, but it is unable to meet our 20 cm stand-off requirement because of its lower beam quality without resorting to much larger lower f/# optics than we think are advisable.

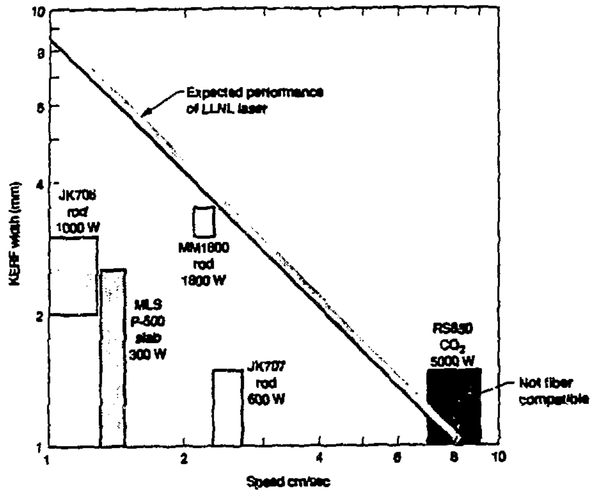

Fig. 5 This comparison of commercial lasers with the RS850 speed does not *restrict them to* meet the stand-off requirement. The RS850 laser is unfortunately not fiber compatible.

Once inside the keyhole, the GE drilling data suggests that the laser pulse forms an index guide. Visible plasmas emerging from the hole have ion temperatures *in the neighborhood of 2 ev.* Wall temperatures, and thus the radiation temperature in the hole, are closer to the vaporization temperature of the metal, about 2000 °K or less than 10% of the ion temperature. Charge neutrality is assured so the electron density mimics the ion density, but temperatures need *not be the same in this non-local* thermodynamic equilibrium plasma. Electron temperatures are probably several ev and the dominant absorption mechanism is likely to be classical collisional absorption or inverse Bremsstrahlung. The spatial damping rate or absorption coefficient for inverse Bremsstrahlung is *highly density* and temperature dependent,

$$\kappa_{ib} = \frac{Zn_e^2}{T_e^{3/2}(1 - n_e/n_c)^{1/2}},$$

where n_e is the electron density, T_e is the electron temperature, Z is the average atomic number of the wall material and $n_c \approx 10^{21}$ electrons/cc is the critical density for 1μm light. Inverse Bremsstrahlung is thus strongest for low temperatures, high densities, and high Z wall materials. The picture which emerges is of a channel in pressure equilibrium with cool high density electrons leading to low index of refraction near the cool *walls and hotter* lower density electrons along the axis of the hole. Such an electron density distribution forms an index guide which would tend to keep a high quality laser beam from interacting with the walls. Inverse Bremsstrahlung in plasma gradients at other than normal incidence goes by the name of resonance absorption. Microwave propagation in the ionosphere suffers from this effect and it has received much theoretical attention over the years. In a plasma having a steep quasi-linear gradient the resonance absorption on reflection is given quantitatively by

$$\phi(\tau) = 2.31\tau\exp(-\frac{2\tau^3}{3}),$$

where $\tau = (kL_e)^{1/3}\sin\theta_i$.[11] The predicted absorption fraction when the laser beam bounces from the wall will be given by $0.5\phi^2$. A preliminary index guiding calculation for 300 μm keyholes suggests that the our notional beam focuses in the hole in about 1 mm after which it diverges to bounce from the keyhole plasma near the wall at a depth of almost 2 mm at an interaction angle of about .04 radians. Such a shallow incidence angle, θ_i, keeps the absorption down to a few percent per bounce even if the electron density scale length, L_e, is tens of μm. If deeper keyholes are desired, this guiding phenomena continues to depc .it energy in the walls at a rate sufficient to maintain the wall temperature at the vaporization point in the face of thermal conduction losses radially. It will take about 1 kWatt per cm of hole depth to maintain a steel wall in this equilibrium state. As a result, the maximum hole depth, limited by wall losses, for a train of 10 J 1 msec laser pulses of the quality we require would be about 10 cm.

Efficiency, reliability and ultimate cost are strongly dependent on technology. The first solid-state industrial lasers which we build for sheet steel welding may well be arc lamp pumped. By far the most attractive option from the user's point of view would be one which gives him a material processing laser system which is compact, efficient, and maintenance free. Laser diode pumped Nd:YAG offers these features to a greater extent than any previous laser.

5.0 Laser crystal availability

Three types of Nd doped crystals having the characteristics we seek in a HAP laser are commercially available today:

US Manufacturers

- Allied Signal Corporation has grown 90 × 200 mm boules of Nd doped GGG and similar sized boules of co-doped Nd:Cr:GSGG. They are currently scaling flat interface YAG crystal growth to comparable sizes. Fig. 6 is a photograph of a YAG crystal slab grown recently by Allied, which already meets the dimensions required for a practical material processing laser, $7 \times 40 \times 200mm^3$.
- Litton Airtron has grown some flat interface Nd:YAG crystals in order to develop techniques for more cost effective laser crystal production.
- Union Carbide has indicated interest but is not able to mount an effort to grow larger laser crystals due to a lack of funding.

Foreign Manufacturers

- Sumitomo Metals and Mining Corporation is offering Nd:GGG crystal boules 90 mm in diameter and over 200 mm long. They also sell Nd:YAG, but in much smaller sizes. Sumitomo, through their subsidiary Lumonics is actively pursuing HAP crystaline laser development.

[11] V. L. Ginsberg, Propagation of Electromagnetic Waves in Plasmas, Gordon and Breach, N.Y.,1960, or Pergamon, N.Y., 1964, Ch 4 and 6

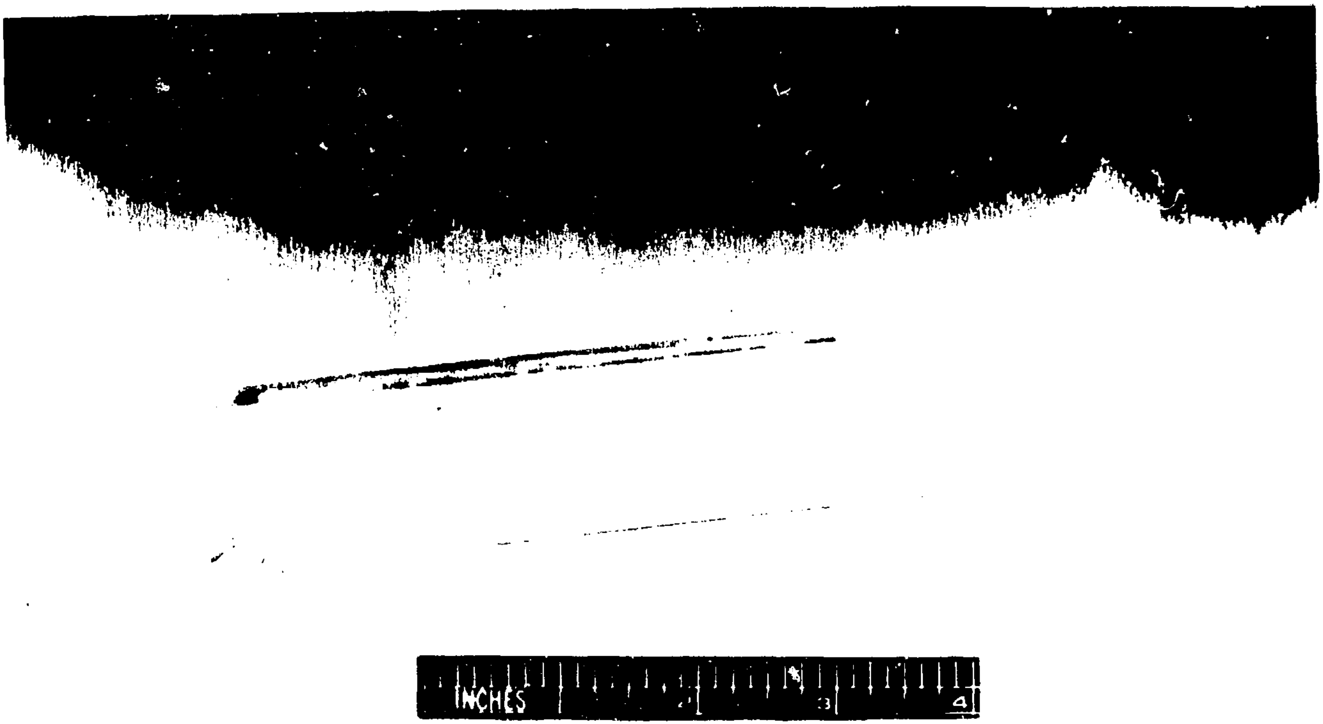

Fig. 6 This Nd:YAG zig-zag slab is $7 \times 4 \times 20$ cm^3

- Wacker Chemitronic, West Germany's largest producer of Si, has grown 80 mm diameter by 200 mm long Cr:Nd:GGG crystal boules which have excellent loss and birefringence characteristics.

In the past, LLNL Advanced Applications programs have collaborated with Allied Signal Crystal Products Division to develop Nd doped garnets of sizes adequate for the HAP missions. Nd:GGG and Nd:Cr:GSGG crystal slabs 5 x 80 x 200 mm^3 in size are now in hand at LLNL, some are even figured into zig-zag slabs, and a program to produce similar sized Nd:YAG showed great promise until it had to be put on hold for lack of funds last year. The three major suppliers of oxide garnet laser crystals in the USA are all under pressure to reduce their research and development budgets precisely at a time when Soviet effort is high, Japanese manufacturers have demonstrated 850 W Nd:GGG lasers, and a West German capability is also emerging. Indeed, the only zig-zag slab laser on the market today is the Munich Laser Systems P500.

6.0 Status of LLNL arc-lamp and diode pumped solid-state laser effort

CONTINUOUS wave Nd:YAG lasers are commonplace, but higher average power or "HAP" crystalline lasers, such as those needed for missions of interest to us here, require some improved technology. Depending on the crystal size used, its temperature, and the available pump power, the repetition rate of the laser amplifier can range up to more than 6000 Hz. Thermal-optical stress calculations show that a Nd:YAG slab 10 × 40 × 200 mm^3 can achieve a gain of 10 at 100 Hz. An oscillator designed for high repetition rates or cw operation might employ 5 × 40 × 200 mm^3 slabs and should have usable gains > 2 at 3000 Hz using vortex stabilized water wall arc lamps. Improved performance is possible using large area laser diode pumping as discussed below.

At 500 Watts of output, the slab laser should already be quite a challenge to EDM manufacturing. In the near future, we expect improved performance as new slab laser models are introduced into the industrial laser market at just about one kilowatt of output from a single Nd:YAG head. A barrier exists at this level chiefly because conventional flashlamp technology is limited to wall loadings of about 300 W/cm^2. Lamp life falls dramatically above a wall loading of about 400 W/cm^2. Though there are gains to be made by increasing the specific power loading in Nd:YAG, conventional lamps are unequal to the task. It was for this reason that we began a search for higher power pump sources. Vortek^{TM} lamps currently survive for several hundred hours at wall loadings of 1.5 kW/cm^2. Laser diode arrays not only are more efficient than lamps, but also they deliver their power at the correct wavelength to pump Nd doped garnets. Scaling up boule growth would allow the fabrication of larger slabs, but without better pumps their potential could not be realized.

At LLNL two Vortek^{TM} arc-lamps have been modified to pulse close to the optimum power density and at arbitrary pulse repetition frequency and duty factor. Fig. 7 is a photograph of our Vortek^{TM} lamp test bed showing a Nd:GGG slab mounted in a cooling fixture. Our diffuse reflector technology has demostrated smooth pumping profiles with no loss of tranfer efficiency and has operated at high average power. Fig. 8 a) compares our diffuse reflector to a silver plated specular reflector and shows that amplifier gain is not reduced using the more forgiving diffuse reflector pumping cavities. Experience has shown that diffuse reflectors are not only less expensive to build, but also less sensitive to the relative location of the lamp with respect to the reflector and the crystal slab and that they produce quite acceptable measured phase distortions as shown in Fig. 8 b). Integrating these technologies, the prototype we are building should produce in excess of two kilowatts of laser power. Fig. 9 contains a comparison of observed fluorescence to calculated deposition using our diffuse reflector simulator. This kind of data serves as a starting point for our TECATE thermo optical simulator. Fig. 10 shows, greatly magnified, the pump induced deformations TECATE predicts will be produced by loading our crystal slabs in our diffuse reflector lamp cavity. TECATE also tells us what to expect when we make interferograms of our slab amplifier. Fig. 11 shows the effects of different end cooling and pumped length strategies on the predicted phase front.

Once the amplifier is ready, our effort must turn to resonator optimization, stressing the achievement

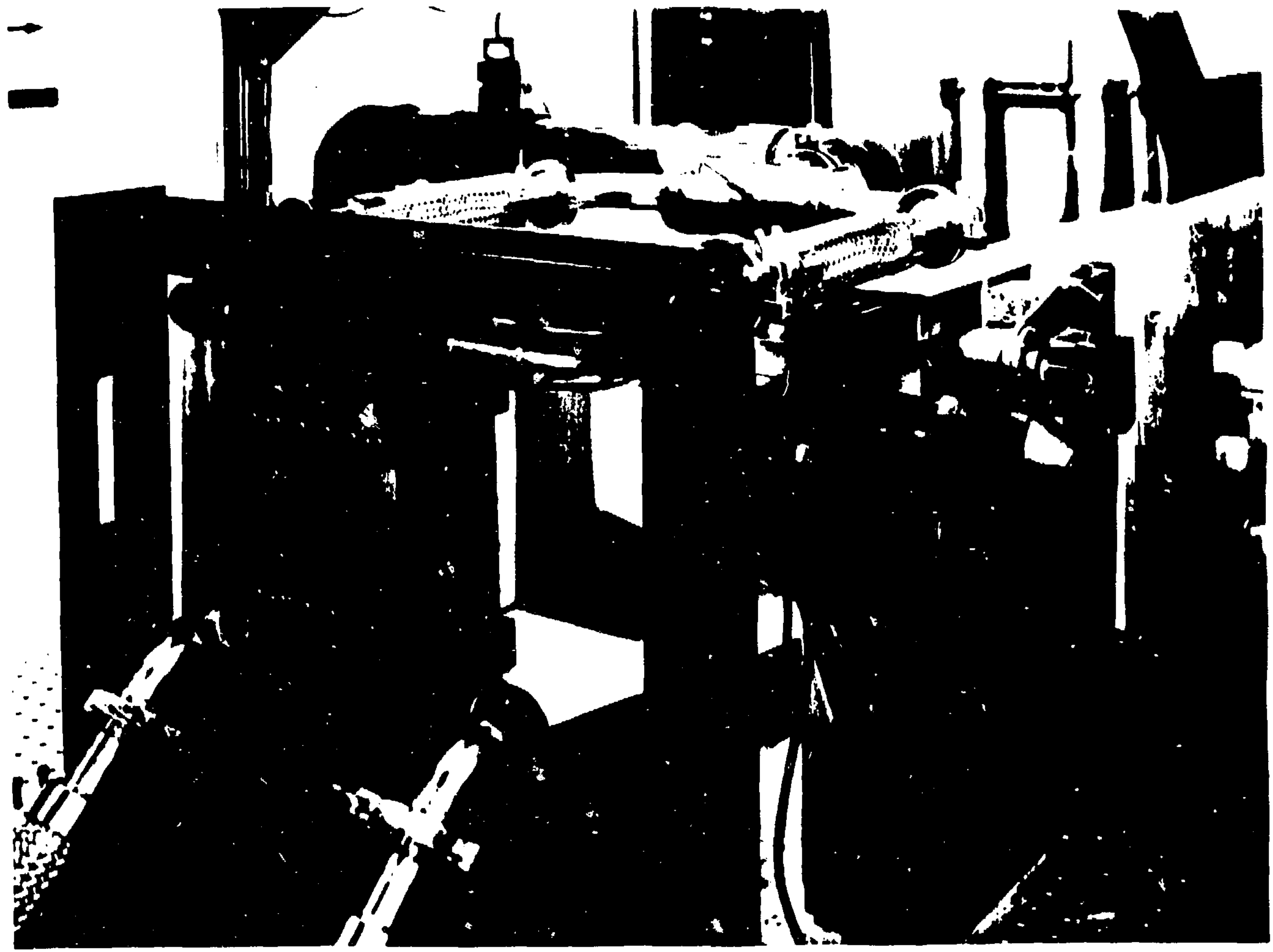

Fig. 7 Vortek^{TM} arc-lamp pumped crystal slab laser test facility

Single Pass Gain–Diffuse v.s. Specular Reflectors

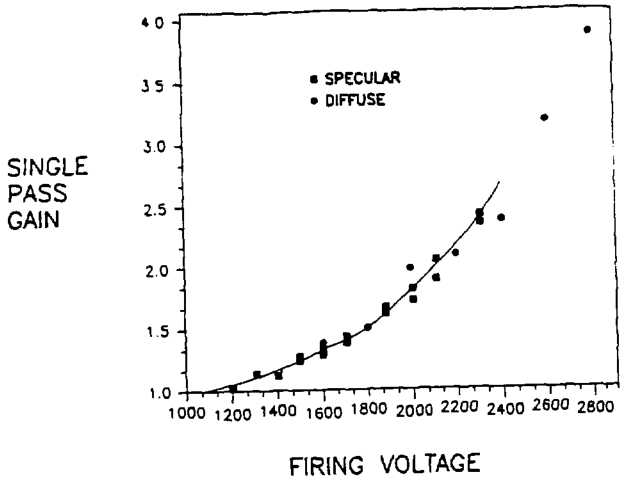

Fig. 8a)

Single Pass Slab Aberration–Diffuse Reflector

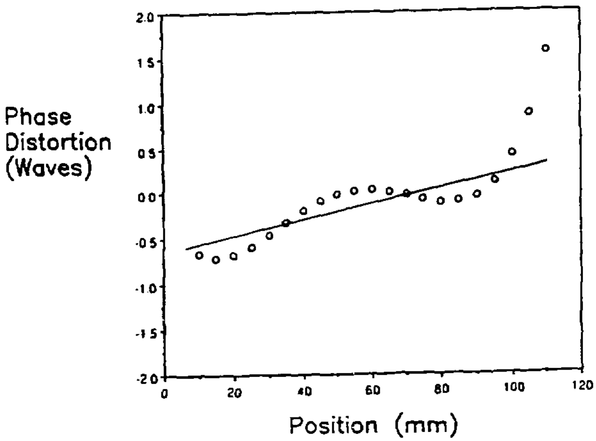

Fig. 8b)

Fluorescence Image v.s. Source Calculation

HISTOGRAM:
CALCULATED
VOLUME
SOURCE

LINE OUTS:
FLUORESCENCE
INTENSITY
x–y PROFILES

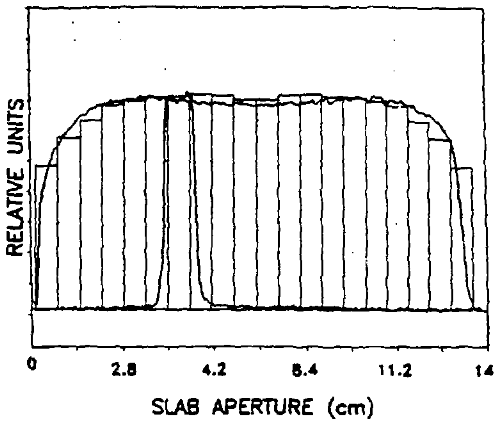

Fig. 9

Vortek pumped GGG, Diffuse Refl, 55 C Ends

Magnification = 3000

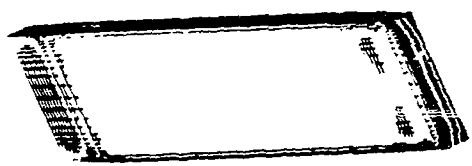

Fig. 10

TECATE—Computed Interferograms

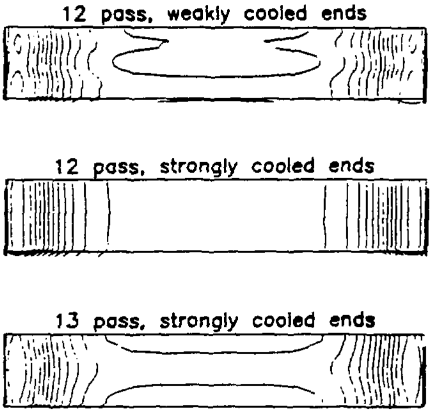

Fig. 11

of high beam quality. We have modeled a supergaussian tapered unstable resonator using OASIS and obtained encouraging results. Measured aberrations were converted to a phase screen and inserted into a tapered mirror unstable resonator simulation as shown in Fig. 12. The predicted output beam focuses to acceptable powers as indicated by Fig. 4. As is well known, efficient frequency conversion of infrared laser light depends on achieving high optical quality. High average power non-linear optics have already been demostrated at LLNL; Q-switching and frequency conversion should also be a part of any program to test the sensitivity of materials processing variables to changes in beam format.[12] In a very few years, however, we contend that diode pumped solid state lasers will carry the field and wavelength conversion of these devices will offer the manufacturing engineer great latitude in working modern materials.

The key issues associated with developing high average power diode pump sources include cost, reliability, and thermal management. LLNL has developed a reliable, low cost packaging technology based on silicon microstructures that is ideally suited for high average power applications. The basic package design is shown in Fig. 13 and features LLNL designed microchannel coolers bonded in a unique LLNL process to Al:GaAs laser diode arrays. Current production levels stand at about eight of these packages per day and can be expanded several fold depending on demand. These packages routinely achieve peak powers of 90 Watts and average powers of 20 Watts. When stacked as shown in Fig. 14, they make compact, high intensity and high average power optical pump sources for solid-state lasers. In order to meet the our welding requirements, we propose to optimize diode array performance for high duty factor optical output, ≈ 0.2, with about two hundred microsecond duration pulses coming at 1000 Hz of 0.8083 μm light and 360 W/cm^2 peak irradiance. Conceding that laser-diode-pumped solid-state devices would be highly desirable, critics often cite exorbitant cost as the reason not even to consider this pumping option. LLNL experience points emphatically in the opposite direction. Current LLNL production costs stand at between \$ 5.00 and \$ 7.00 per peak watt and should drop rapidly as volume increases.

A high power diode-pumped solid-state laser test bed, depicted in Fig. 15, supplements our Vortek^{TM} arc-lamp pumped test bed. The compact device shown used ten diode pumping packages to produce a 40 W laser beam at 1.064 μm. Life testing so far has shown no degradation after several billion shots; however, we feel that the most important near term task to be addressed would be to scale this device to over 200 Watt average power performance and conduct life tests. LLNL's diode array package should operate about 10,000 hrs without any maintenance. It is tolerant of rapid cycling on and off, and a diode pumped solid-state laser's turn on transient period of 10's of seconds will be dominated by thermal equilibration of the crystalline slab itself.

LLNL remains the only major R&D effort on HAP crystalline lasers in the USA, and very likely the only laboratory capable of building a diode-pumped HAP crystalline laser suited to industrial needs for the next year. There is sharp competition in this rapidly developing field, however, and a failure to apply what we at LLNL have learned may have very negative consequences for US industry. Fig. 16 contains a conceptual design for a 2 kW average power, 8 kW peak power diode-pumped solid-state laser which might package into a unit like that sketched in Fig. 17 with a foot print of only 40 cm by 50 cm. In summary, an industrial laser whose optics and power supply would fit into a volume roughly equal to that used by current much lower power solid state lasers, is on the horizon. The possessor of this technology will be able to cut and weld sheet steel structures like automobile bodies with significantly lower cost and improved reliability than will a competitor constrained to today's methods including CO_2 lasers.

Work performed by the Lawrence Livermore National Laboratory under the auspices of the U. S. Department of Energy under Contract W-7405-Eng-48.

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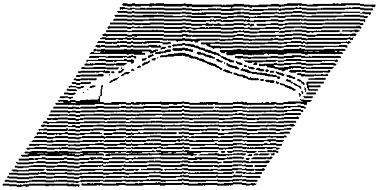
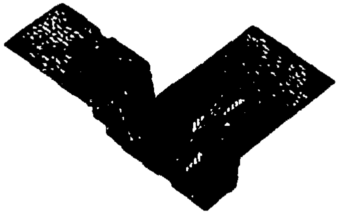
[12] L. F. Weaver, C. S. Petty, and D. Eimerl, *Multikilowatt Pockels cell for high average power laser systems*, J. Appl. Phys. 68 (6), 15 Sept. 1990

Interferometric measurement of Zig-zag slab optical quality is input to OASIS



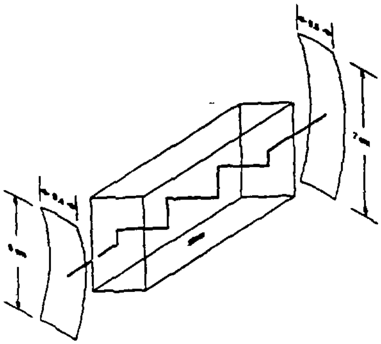
ZAP scan of
ND:GGG slab



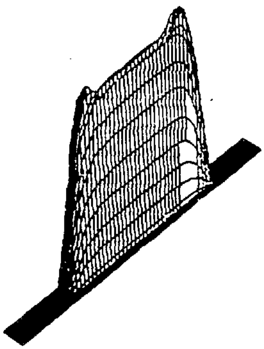
OASIS
Phase screen

AA KFM 8/90 4

Tapered reflectivity unstable resonators should produce excellent beams in a compact cavity



Phase screen in
center of cavity



OASIS simulation
of output beam

AA KFM 8/90 5

Fig. 12

Key issues associated with developing high average power diode pump sources are cost, reliability, and thermal management

- Livermore has developed a reliable, low cost packaging technology based on silicon microstructures that is idealy suited for high average power applications

- basic package design:

current production level - 8 per day
peak power - 90 watts
average power - 20 watts
irradiance - 80 W/cm^2

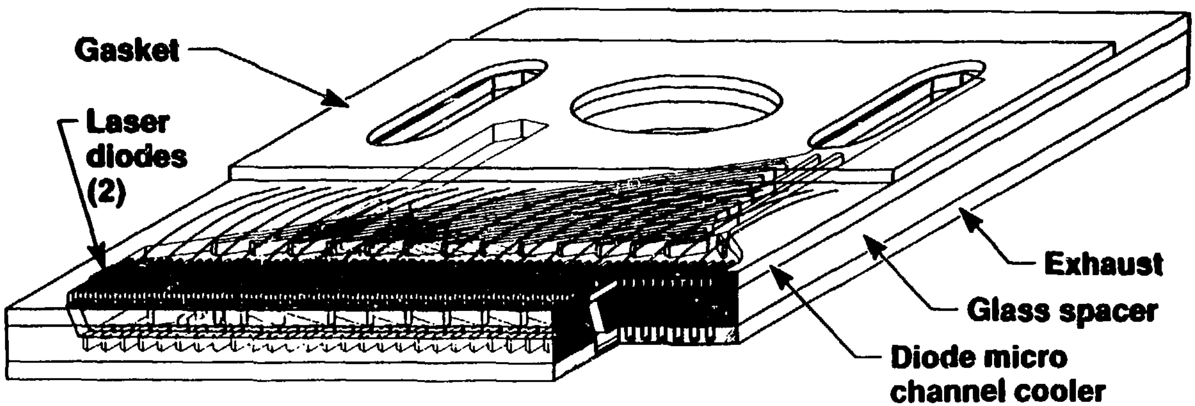
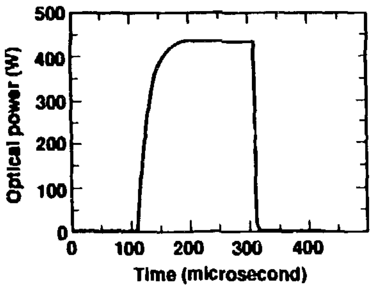


Fig. 13

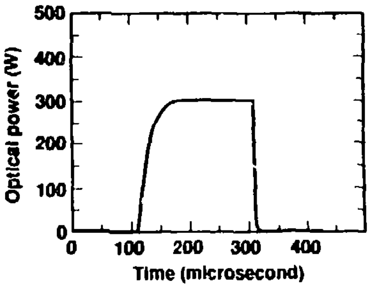
Compact, high intensity and high average power optical pump sources for solid state lasers

Basic unit
- Wafer thin
- Stackable
- Low thermal impedance

Compact, high power, pump array
5 basic units stacked together
Series electrical – cooled in parallel

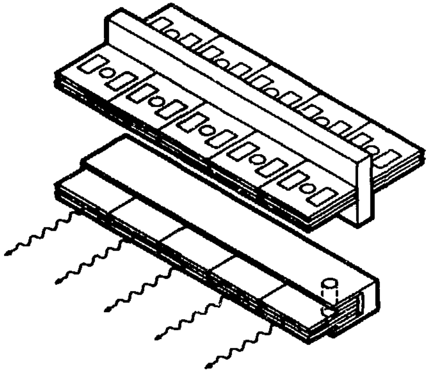


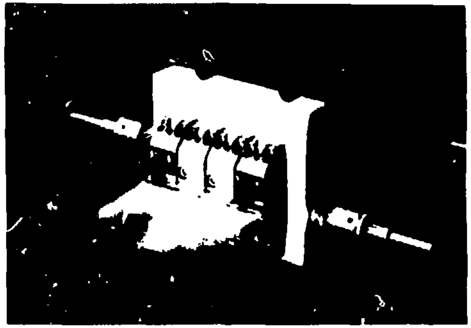
Low duty factor optical output
140 amps @ 10 Hz

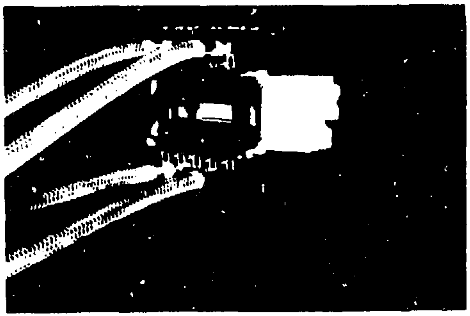


High duty factor optical output
130 amps @ 2.5 kHz
Average optical power 80 W/cm^2

High power diode pumped solid state laser test bed







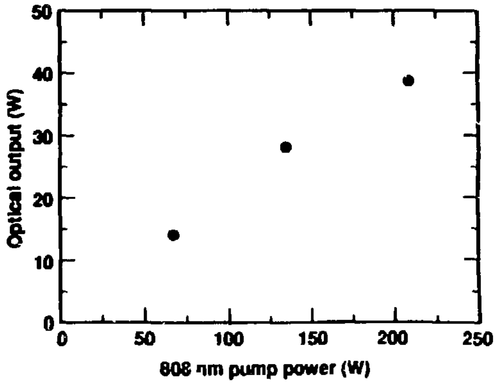


Fig. 15

Conceptual design for 2 kW average, 8 kW peak power diode pumped solid state laser

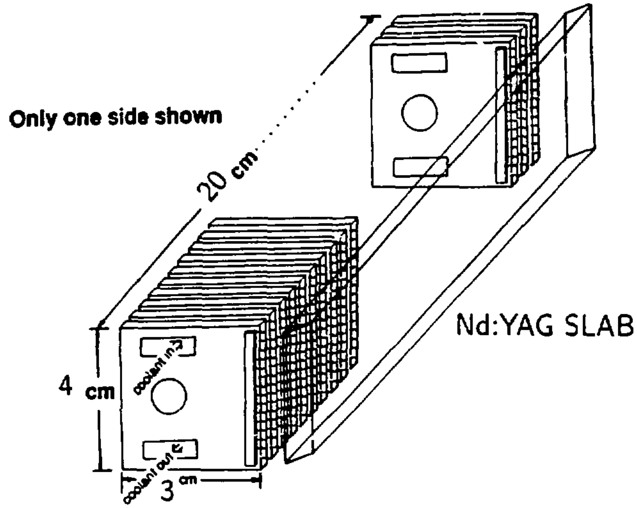


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Fig. 16

Diode pumped GGG amplifier

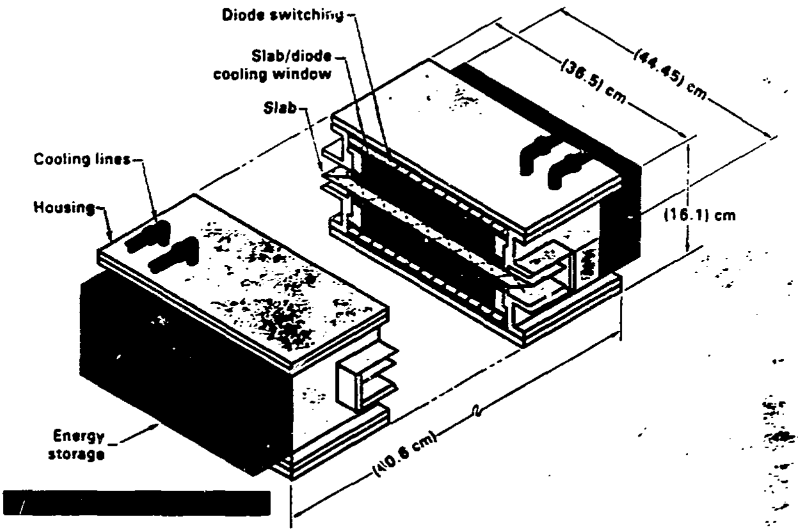

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Fig. 17