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SOLID STATE LASER DRIVER FOR AN ICF REACTOR*

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ABSTRACT

A conceptual design is presented of the main power amplifier of a multi-beamline, multi-megawatt solid state ICF reactor driver. Simultaneous achievement of useful beam quality and high average power is achieved by a proper choice of amplifier geometry. An amplifier beamline consists of a sequence of face-pumped rectangular slab gain elements, oriented at the Brewster angle relative to the beamline axis, and cooled on their large faces by helium gas that is flowing subsonically.[1] The infrared amplifier output radiation is shifted to an appropriately short wavelength (<500 nm) using nonlinear crystals that are also gas cooled. We project an overall driver efficiency >10% (including all flow cooling input power) when the amplifiers are pumped by efficient high-power AlGaAs semiconductor laser diode arrays.

INTRODUCTION

An economic ICF reactor requires[2] that the driver have a nominal output power of a few tens of megawatts at a short wavelength (<500 nm), an efficiency >10%, and an installed capital cost of <50$/optical watt. It has long been presumed that a laser driver using a solid state gain medium would be unable to meet any of these operating levels: removal of waste heat could not be accomplished in a manner simultaneously permitting useful beam quality; solid state lasers are typically only a few percent efficient; the cost issue is therefore moot.

These presumed limits have been critically reviewed and found to be spurious[1,3]. These analyses indicate that: 1) megawatt class laser systems with useful beam quality <u>can</u> be built using the proper <u>geometric</u> <u>configuration</u> for the solid state power amplifier elements and the associated cooling subsystem. As shown schematically in Fig. 1, such a power amplifier consists of a sequence (two shown) of rectangular solid state gain slabs that are oriented alternately at Brewster's angle with respect to the beamline axis. Each slab is optically pumped through its two large faces, and is cooled by helium gas flowing subsonically over these faces. 2) An overall driver efficiency >10% <u>can</u> be obtained using AlGaAs semiconductor laser diodes as pump sources.[4] Individual high power laser diodes have recently operated[5] with an efficiency of 57% and are expected to reach 70%; a 2-D array of laser diodes has produced[6] an optical power flux >3 kW/cm^2 in pulses of ~150 microseconds duration; diode arrays have also been operated[7] repetitively at tens of Hz, producing >3x10^9 pulses (commensurate with the operating life of an ICF power plant). 3) The cost of a solid state ICF driver now becomes a relevant issue (as it is with all of the other ICF driver candidates), in light of these two technical innovations.

During the past two years, an experimental, theoretical, and computational effort[8] has been undertaken at LLNL to assess the thermo-optical performance potential of the gas-cooled, Brewster angle slab laser architecture. A product of this effort has been the creation and validation of computer and analytic models with which to design optimized high average power solid state lasers.[9] The results to date confirm earlier simple estimates of power scaling[1,3] and are used to support the conceptual design of an ICF reactor driver presented in this paper. For concreteness in the design, we adopt neodymium/yttrium doped calcium fluoride[10,11] as the solid state gain medium. This author judges that this crystalline material could be produced in the required size, optical quality, and $/cc cost, based on current development trends[12-15]. It also possesses the physical and quantum electronic properties sufficient to achieve the operating energy, power, and efficiency levels sought in an ICF reactor driver.

In the remainder of this paper, we describe the principal optical and thermo-mechanical characteristics of the main power amplifier of a solid state ICF driver. We first describe the gain slab and its gas cooling subsystem. We then give a description of an amplifier beamline and a cluster of beamlines forming a megawatt-class power amplifier module. Concluding remarks are centered on system cost issues and the identification of research areas that can significantly reduce system cost and increase performance.

THE SOLID STATE GAIN ELEMENT

The basic gain element of this point design is a rectangular slab made of single crystal calcium fluoride (CaF_2), doped with nominally 1.5 and 7x10^{20} ions/cc of neodymium (Nd^{3+}) and yttrium (Y^{3+}), respectively. The design assumes slab dimensions of 30 cm width, 53 cm length, and 2 cm thick. The pump absorption coefficient and plate thickness together to result in a 95% absorption of pump energy. The resulting moderate gain gradient is normal to the plate face, at a constant small angle to the extraction beam direction. It therefore will cause negligible beam distortion. The relevant thermal, optical, and mechanical properties of CaF_2 are given in Table 1, along with the salient

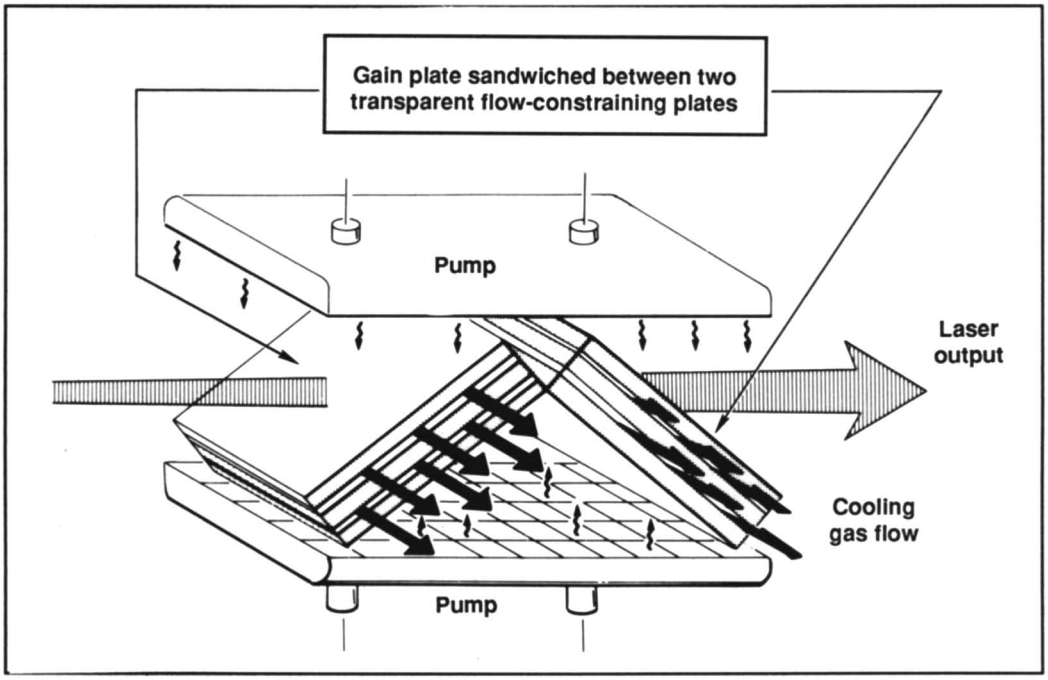

Figure 1
Gas Cooled Slab (GCS) Amplifier

spectroscopic[11] properties of Nd:Y:CaF$_2$. The thermal shock resistance parameter $R_T=(1-\upsilon)(S\kappa)/(\alpha E)$, is a key quantity that characterizes the maximum thermal gradient that a material can carry without mechanical failure. The bending strength, S, is not an intrinsic property of the material, but depends on the surface preparation techniques (size and distribution of flaws)[16]. The value cited in Table 1 is for optically polished CaF$_2$ laser windows[7]; breaking strength values up to ~26 kspi have been attained[17] with special post preparation anneal techniques. For undoped CaF$_2$, R_T=3.3 W/cm for the values given in Table 1, and may be increased several fold by improved finishing techniques. Taking into account somewhat increased breaking strength and somewhat decreased thermal conductivity for Nd:Y:doped CaF$_2$, a thermal shock value for Nd:Y:CaF$_2$ of ≥2.5 W/cm is expected. This R_T value is relatively modest compared to the more robust oxide crystals, such as YAG and sapphire. Yet it is sufficiently large to allow the thermal load applied in the present design, calling for operation at ≤20% of stress fracture.

TABLE 1
PHYSICAL AND SPECTROSCOPIC CHARACTERISTICS OF CALCIUM FLUORIDE

PARAMETER	VALUE
Thermal expansion, α	20×10^{-6}/*C
Young's Modulus, E	11 Mpsi
Bending strength, S	~15 kpsi
Thermal conductivity, κ	0.1 W/cm
Poisson's ratio, υ	0.3
Thermal Shock Resist., R_T	~3.3 W/cm
Index of refraction, n	1.43
Nonlinear refractive index, n_2	6×10^{-14} esu
Emission cross section, σ_L	~2×10^{-20} cm^2
Saturation fluence, Γ_s	10 J/cm^2
Radiative lifetime, τ_{rad}	~600 msec
Mean pump cross section, σ_p	~1×10^{-20} cm^2

The physical and laser related parameter values of the gain slab are given in Table 2. The values adopted represent a rational design point taking into account all of the usual constraints due to gain, saturation, amplified spontaneous emission, parasitics, etc. The associated pump array operating values are presented in Table 3. The pump pulse duration of 260 microseconds is set to 45% of the fluorescence decay time, thus limiting the energy fluoresced away while pumping to 20%. The stored energy density of 0.48 J/cc and the pump pulse duration of 260 microseconds result in a fairly high pump array flux of 3.8 kW/cm^2. While clearly achievable (3.3 kW/cm^2 has been demonstrated[5]) there is an associated issue of array shot life at this flux level. It is assumed here that high flux array life can be increased with further development; alternatively, the array flux can be reduced by oversizing the array area and accepting a less compact structure. Note from Table 2 that the gain medium is subjected to a specific thermal loading of only 1.5 watt/cc. Because this heat is removed from both slab faces, the required surface heat removal flux is only 1.5 watt/cm^2 for the 2 cm thick slab. Note also that the optical power available at 1060 nm, per unit volume of slab, is about 3 times the slab thermal power density; thus the gain slab is capable of generating an output power of about 4.5 watts/cc at 1060 nm.

TABLE 2
GAIN SLAB CHARACTERISTICS

PARAMETER	VALUE
Width, W	30 cm
Length, L	53 cm
Thickness, t	2 cm
Face area, A	1600 cm^2
Volume, V	3200 cm^3
Doping Density, ρ	$1.5 \times 10^{20}/cm^3$
Absorp. Coeff., αpump	1.5 cm^{-1}
Inversion Density, ΔN	$2.5 \times 10^{18}/cm^3$
Gain Coefficient, aL	0.05/cm
Stored Energy Density, E_s	0.48 J/cm^3
Stored Energy, Ep	1500 J
Single pass gain, $1.22a_Lt$	12.2%
Transverse Gain, a_LLn	3.8
Absorbed Pump Fraction	0.95
thermal loading factor, χ	0.3
Heat Energy Density, Q	0.15 J/cm^3
Pulse Repetition Rate, R_p	10 Hz
Heat Power Density, P_v	1.5 W/cm^3
Surface Heat Flux, ϕH	1.5 W/cm^2

TABLE 3
PUMP DIODE ARRAY CHARACTERISTICS

PARAMETERS	VALUE
Pulse Duration	260 msec
Geometric Area	1300 cm^2
Flux	3.8 kW/cm^2
Fluence	1.0 J/cm^2
Efficiency	~60%
Duty Factor	0.0026

THE SLAB GAS COOLING SUBSYSTEM

Figure 2 shows a sketch of a gas cooled slab assembly. The rectangular gain element is sandwiched between two transparent plates to form 2-D cooling channels. Turbulent cooling gas is flowed across the width of the slab, picking up slab waste heat from the large faces. The slab assembly is oriented at the Brewster angle relative to the axis of the optical extraction beam. To form a beamline, a number of slab assemblies is sequenced along the optical axis with their Brewster angle tilt directions alternating so that the output beam axis is insensitive to precise angular orientations of the individual slab assemblies. The optimum channel dimensions, choice of cooling gas, and gas flow conditions are dependent on many factors, including 1) the surface heat flux to be removed, 2) the tolerable amount of loss and wavefront distortion due to turbulence scattering in the flow channel and in the drift region between adjacent slab assemblies, and 3) the degree to which the overall system efficiency is reduced by the consumption of power to perform the cooling function. Quantitative measurements[9] of optical beam quality in the channel region have been made for a wide range of surface heat fluxes, gas pressures, channel dimensions, and gas flow parameters. The insert in Fig. 2 shows a blow-up of the flow channel region and indicates typical parameters for efficient cooling: a flow channel width of a few millimeters, helium cooling gas at 2-3 atmospheres of pressure, a flow Mach number of less than 0.1, with gas flow along the shorter dimension of the slab face. In the present fusion driver point design, the surface heat flux is 1.5 watts/cm^2, a very comfortable operating point. The optical output flux is about 6 watts/cm^2 of slab area. Since the optical fluxes available from each of the slabs in the beamline add together, a beamline consisting of tens of slabs can produce 100-200 watts output power per cm^2 of beamline aperture. Tables 4 and 5 give design point parameter values for gas flow in the channel and drift regions, respectively. The total input power needed to move the cooling gas through the channel and drift regions, extract heat added to the gases via heat exchangers, and to recondition the gas for another cooling cycle is calculated to be only 3.1% of the electrical input power required to produce the laser output power. (The power required to water cool the pump diode arrays is estimated to be negligible, as is the power required to cool the harmonic converter crystals)

TABLE 4
FLOW CHANNEL CHARACTERISTICS

PARAMETER	VALUE
Cooling Gas	Helium
Channel Thickness, h	3.7 mm
Pressure, P	2.75 atm
Pressure Head	~10 torr
Flow Mach Number, M	0.06
Inlet Temperature, T_{in}	300 K
Outlet Temperature, T_{out}	310 K
Turbulent Scatter Fraction	$<<10^{-3}$
Slab Center Temperature, T_c	350 K

TABLE 5
DRIFT REGION CHARACTERISTICS

PARAMETER	VALUE
Cooling Gas	Helium
Pressure, P	2.75 atm
Pressure, Head	~10 torr
Bulk flow Velocity, v	ë1 m/sec
Turbulent Scatter Fraction	$<< 10^{-3}$
Surface Solidity	98-99%

AMPLIFIER BEAMLINE

The number of slabs in a laser beamline is determined by several factors, including 1) the single-pass small-signal-gain and non-saturable loss, 2) the gain saturation fluence, 3) the optical damage fluence, and 4) diffraction and nonlinear index beam propagation effects. The present point design uses 30 gain slabs in the beamline as a reasonable tradeoff among these factors. Table 6 gives a summary of the characteristics of a single

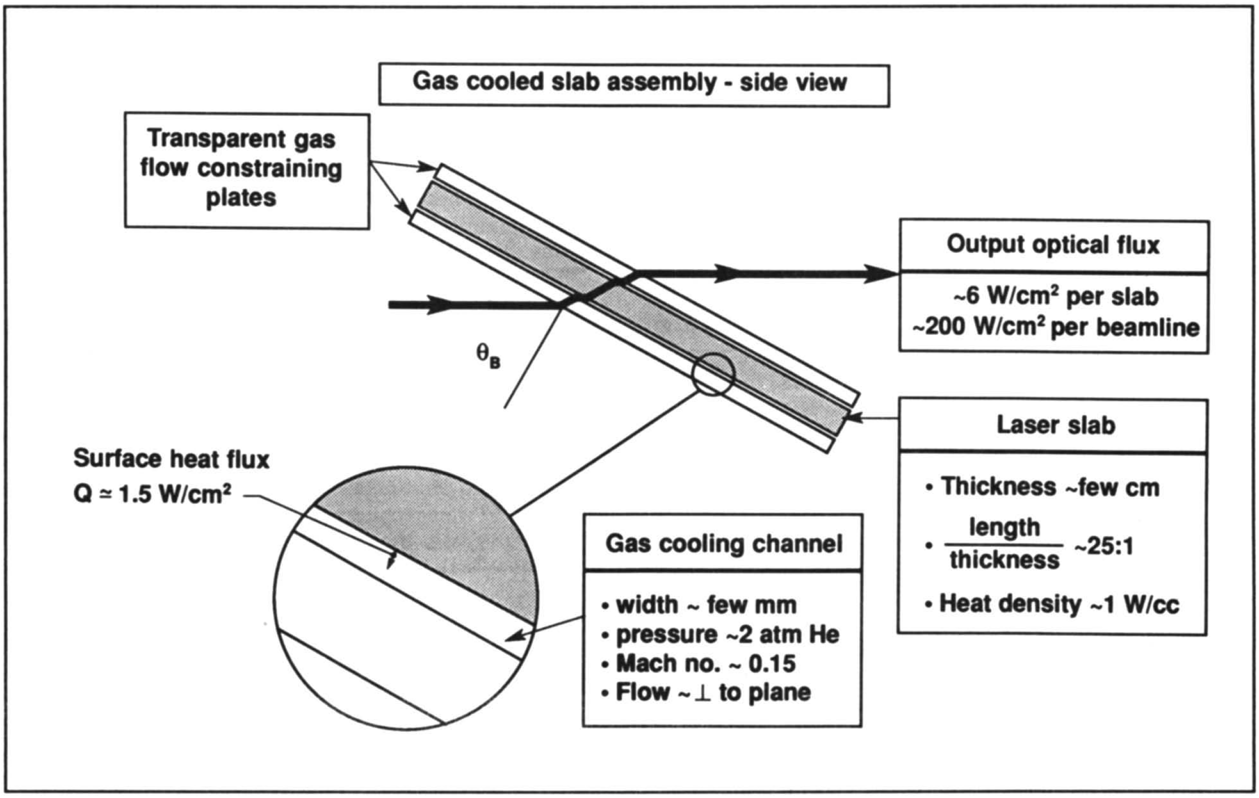

Figure 2
GCS Characteristics

amplifier beamline (28 x 28 cm² clear aperture). Such a beamline generates a pulsed output energy of 25 kJ in a 10 nsec pulse, at a repetition rate of 10 Hz, for an 1060 nm average output power of 250 kW. The slab output fluence of 20 J/cm² is moderately high in this design (in relation to LLNL measured damage thresholds in alkaline earth fluorides as high as ~30 J/cm² at 10 nsec). Higher damage thresholds are anticipated in fluoride crystals with further refinement in fluoride crystal growth. If this expectation is not realized, a long shot life system would require moving off this design point to a somewhat lower output fluence. The calculated scatter losses in the channel and drift regions are negligible (<<0.1% per slab assembly) in relation to the single pass slab gain (12%). Detailed analysis of flow and heat transfer induced optical distortions in a suitably constructed slab assembly shows these effects to be dominated simply by the optical figure of the individual elements. Assuming that these surfaces are finished flat to a twentieth of a wavelength, it is estimated that the output beam quality will be better than three times diffraction limited.

TABLE 6
AMPLIFIER BEAMLINE CHARACTERISTICS

PARAMETERS	VALUE
Clear Output Aperture	28 x 28 cm²
Number of Gain Slabs	30
Single Pass Gain	3.66
Single Pass Power Gain, Exp G	38
Total Stored Energy	45.6 kJ
Extraction Efficiency	0.7
Fill Factor, η_{fill}	0.8
Output Pulse Energy	25 kJ
Output Average Power	250 kW
Output Fluence In Slab	20 J/cm²
B-Integral	2.3 radians

An estimate of the efficiency of an amplifier beamline is given in Table 7, expressed as a product of sub-efficiency factors representing the flow of power from the diode pump arrays, through the gain medium, to the 1060 nm output beam, and finally to harmonically converted 350 nm radiation. The asserted sub-efficiency values are based on experience with present Nd:glass fusion lasers, and/or on analytical estimates of what might reasonably be anticipated in the future. The projected efficiency of 15% is an attractive performance level for the fusion reactor application, if it can be realized practically. Long lived 60% efficient diode arrays are certainly not available now, but they well may be ten years from now when a more intensive development of ICF drivers is underway. On the other hand, 40% efficient, long lived diode arrays of moderate flux are already available and could support an ICF driver with an efficiency >10%. Thus we view these projections of performance as encouraging.

TABLE 7
POWER AMPLIFIER EFFICIENCY PROJECTION

Efficiency Factor	Projected Value
Pump Array Efficiency	0.60
Transport Efficiency	0.95
Absorption Fraction	0.95
Quantum Defect, λpump/λlaser	0.76
Fraction Retained While Pumping	0.80
Energy Storage Efficiency	π0.33
Extraction Efficiency	0.70
Fill Factor	0.80
Conversion to 350 nm	0.85
Flow Cooling Factor	0.97
Amplifier System Efficiency	π0.15

POWER AMPLIFIER MODULE

In this point design, it is envisioned that 16 beamlines, each containing 30 slabs, would be clustered together in an amplifier module consisting of a four by four array (see Fig. 3). Independent channel and drift region flow loops have been laid out for the beamlines and packaged into a fairly compact footprint. This amplifier module would be capable of generating 340 kJ of 350 nm light in a 10 nsec pulse, ten times a second, for an average power of 3.4 megawatts. A gigawatt electric fusion reactor power would require roughly ten such modules.

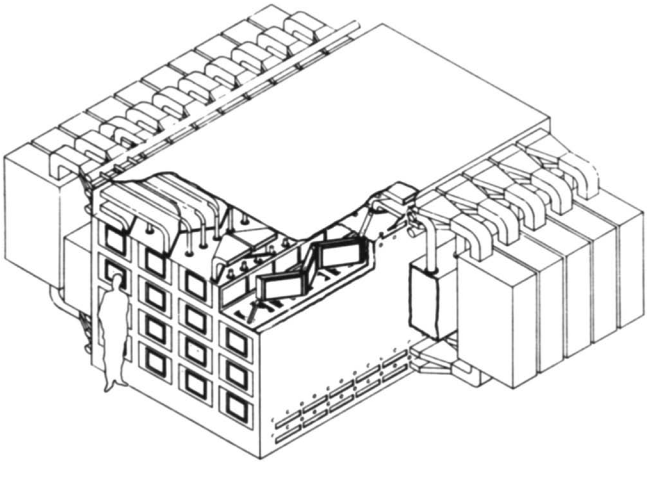

Figure 3
Layout of a megawatt class power amplifier central to an ICF reactor driver, (designed by G. Albrecht, S. Sutton, and S. Mills). 10 of 30 slabs of each beamline are shown.

SYSTEM COST ISSUES

While the present laser system could technically deliver power and energy suitable for an ICF reactor driver, it could not currently do so at a reasonable cost. A major cost driver is associated with the cost of semiconductor laser diode arrays and the degree to which their output power is utilized. The present point design is severely limited in array power utilization due to the relatively short energy storage lifetime (600 microseconds) of the gain medium. When coupled with a reactor repetition rate of 10 Hz, a very low array duty factor of only 0.0026 results. However, the pump arrays can operate at a much high duty factor (~0.1). Thus, the cost effective utilization of diode arrays can be increased in proportion to the increase in energy storage lifetime of the gain medium. Solid state media doped with ions such as Tm^{+3}, Ho^{+3}, Er^{+3} exhibit storages lifetimes in the 5-10 msec range[18], can be efficiently pumped with AlGaAs diode lasers[19], and possess otherwise useful laser parameters for application. The infrared (~1800 nm) output radiation can be converted to ~450 nm wavelength, using 4th harmonic conversion crystal (instead of 3rd harmonic, as in the present design); research on such media is in progress.

Today's cost of laser diodes (~k$/watt) is determined by the present small demand. In a fusion reactor power economy, the annual power demand would be in the 10^8-10^9 watt range, and the unit cost will decrease by many orders of magnitude. Preliminary estimates (proprietary to several laser diode development companies) of unit costs in such a market are sufficiently compelling to warrant further development of this driver concept.

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LLNL colleagues Georg Albrecht and Steve Sutton are responsible for the experimental, computational, and analytical basis for the design of gas cooled, high-power, solid state lasers. Their many contributions to the present work are greatfully acknowledged.

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