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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. 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 requires² 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 $<50\$/\text{optical watt}$. 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 moot, in view of the former tenants.

These presumed limits have been critically reviewed^{1,3} and found to be spurious. These analyses indicate that: 1) megawatt class laser systems with useful beam quality can be

Figure 1. Gas Cooled Slab (GCS) Amplifier

built using the proper geometric configuration for the solid state power amplifier elements and the associated cooling subsystem. As shown schematically in Figure 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 $>10\%$ can be obtained using AlGaAs semiconductor laser diodes as pump sources.⁴ Individual high power laser diodes have recently operated⁵ with an efficiency of 57% and are expected to reach 70%; a 2-D array of laser diodes has produced⁶ an optical power flux $>3\text{ kW}/\text{cm}^2$ in pulses of ~ 150 microseconds duration; diode arrays have also been operated⁷ repetitively at tens of Hz, producing $>3 \times 10^9$ 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.

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During the past two years, an experimental, theoretical, and computational effort⁸ 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 doped crystalline material is judged to be producible in the required size, optical quality, and \$/cc cost. 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 that is proliferated throughout the amplifier, and its gas cooling subsystem. This is followed by 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 system 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 10×10^{20} ions/cc of neodymium (Nd^{3+}) and yttrium (Y^{3+}), respectively. The design assumes slab dimensions of 30 cm in width, 53 cm in length, and 2 cm thick. The relevant thermal, optical, and mechanical properties of CaF_2 are given in Table 1, along with the salient spectroscopic properties of $\text{Nd}:\text{Y}:\text{CaF}_2$. From a thermal design point of view, the thermal shock resistance parameter $R_T = (S_k)/(\alpha)(1-\nu)$, is a key quantity that characterizes the maximum thermal loading that a material can carry without mechanical failure. For CaF_2 , $R_T = 2.5$ watts/cm is relatively small value compared to robust oxide crystals such as YAG and sapphire, yet it is sufficiently large to allow the thermal loading applied in the present driver design. The stress operating point is 20% of the stress fracture limit for CaF_2 .

TABLE 1. PHYSICAL AND SPECTROSCOPIC CHARACTERISTICS OF CALCIUM FLUORIDE

PARAMETER	VALUE
Thermal expansion, α	$20 \times 10^{-6}/^\circ\text{C}$
Young's Modulus, E	11 Mpsi
Bending strength, S	~15 kpsi
Thermal conductivity, κ	0.1 W/cm
Poisson's ratio, ν	0.3
Thermal Shock Resist., R_T	~2.5 W/cm
Index of refraction, n	1.43
Nonlinear refractive index, n_2	6×10^{-14} esu
Emission cross section, σ_L	$\sim 2 \times 10^{-20}$ cm ²
Saturation fluence, I_s	10 J/cm ²
Radiative lifetime, τ_{rad}	~600 μsec
Mean pump cross section, σ_p	$\sim 1 \times 10^{-20}$ cm ²

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	$1.5 \times 10^{20}/\text{cm}^3$
Absorp. Coeff., α_{pump}	1.5 cm^{-1}
Inversion Density, ΔN	$2.5 \times 10^{18}/\text{cm}^3$
Gain Coefficient, α_L	0.05/cm
Stored Energy Density, E_s	0.475 J/cm ³
Stored Energy, E_p	1500 J
Single pass gain, $1.22\alpha_L L$	12.2%
Transverse Gain, $\alpha_L L$	3.8
Absorbed Pump Fraction	0.95
thermal loading factor, x	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, Φ_H	1.5 W/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 15%. The stored energy density of 0.475 J/cc and the pump pulse duration of 260 microseconds result in a fairly high pump array flux of 3.8 kW/cm². While clearly achievable (3.3 kW/cm² has been demonstrated⁵) 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/cm² 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.

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 measurements⁹ 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 0.15, 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/cm², a very

Figure 2. GCS Characteristics

TABLE 3. PUMP DIODE ARRAY CHARACTERISTICS

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

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

TABLE 4. FLOW CHANNEL CHARACTERISTICS

PARAMETER	VALUE
Cooling Gas	Helium
Thickness (constant), h	3.7 mm
Pressure, P	2.75 atm
Pressure Head, $\Delta P/P$	~10 torr
Flow Mach Number, M	0.058
Inlet Temperature, T_{in}	300 K
Outlet Temperature, T_{out}	310 K
Turbulent Scatter Fraction	<<10 ⁻³
Slab Center Temperature, T_c	349 K

TABLE 5. Drift Region Characteristics

PARAMETER	VALUE
Cooling Gas	Helium
Pressure, P	2.75 atm
Pressure, Head, $\Delta P/P$	~30 torr
Bulk flow Velocity, v	≤ 1 m/sec
Turbulent Scatter Fraction	<<10 ⁻³
Surface Solidity	98-99%

the channel and drift regions, respectively. The total input power needed to perform all cooling functions (move cooling gases through the channel and drift regions, extract heat added to the gases via heat exchangers, recondition the gases for another cooling cycle) is calculated to be only 3.1% of the electrical input power required to produce the laser output power.

AMPLIFIER BEAMLINE

The number of slabs in a laser beamline is determined by a number of 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 amplifier beamline (28 x 28 cm^2 clear aperture). Such a beamline generates a

TABLE 6. AMPLIFIER BEAMLINE CHARACTERISTICS

PARAMETERS	VALUE
Clear Output Aperture	28 x 28 cm^2
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/cm^2
Output Fluence, Exit Beam	35 J/cm^2
B-Integral	2.3 radians

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 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%). The output beam quality will be determined principally by the optical figures of the slab and flow-constraining plates in the beamline. 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.

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

TABLE 7. Power Amplifier Efficiency Projection

Efficiency Factor	Projected Value
Pump Array Efficiency	60
Transport Efficiency	0.95
Absorption Fraction	0.95
Quantum Defect, $\lambda_{\text{pump}}/\lambda_{\text{laser}}$	0.76
Fraction Retained While Pumping	0.80
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Energy Storage Efficiency	≈ 0.33
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Extraction Efficiency	0.70
Fill Factor	0.80
Conversion to 350 nm	0.85
Flow Cooling Factor	0.97
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Amplifier System Efficiency	≈ 0.15

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.

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 Figure 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 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 Y. Oster, G. Albrecht, and S. Sutton).

SYSTEM COST ISSUES

While the present laser system could arguably deliver power and energy suitable for an ICF reactor driver, it manifestly could not do so at a reasonable cost. The single dominant 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 (580 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. The pump arrays, which technically can run at a much high duty factor (~ 0.1), are mostly turned off in the present design. 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 gain media with storage lifetimes in the 5-10 msec range (and with otherwise suitable laser parameters) is judged to be realizable and research on such media is underway.

With respect to cost of arrays, today's unit cost (many tens of k\$ per cm^2) is determined by the vanishingly small demand. In a fusion reactor power economy, the annual array demand would be in the 10^7 - 10^8 cm^2 range, and the unit cost will decrease by many orders of magnitude. Preliminary estimates 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 greatly acknowledged.

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