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The Search for Solid State Fusion Lasers

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Abstract

Inertial confinement fusion (ICF) research puts severe demands on the laser driver. In recent years large, multibeam Nd:glass lasers have provided a flexible experimental tool for exploring fusion target physics because of their high powers, variable pulse length and shape, wavelength flexibility using harmonic generation, and adjustable focus. Advances in solid-state laser technology indicate that (1) Nd:glass lasers can be scaled up to provide a single-pulse, multi-megajoule, high-gain laboratory microfusion facility, and (2) gas-cooled slab amplifiers with laser diode pump sources are viable candidates for an efficient, high repetition rate, megawatt driver for an ICF reactor. In both applications, requirements for energy storage and energy extraction drastically limit the choice of lasing media. Nonlinear optical effects and optical damage are additional design constraints. New laser architectures applicable to ICF drivers and possible laser materials, both crystals and glasses, are surveyed.

1. Introduction

Inertial confinement fusion, in which a fuel capsule containing deuterium and tritium is compressed to high density and a thermonuclear reaction ignited, has been the subject of intensive investigation since the early 1970s [1]. The interest in ICF is multifaceted: for basic research in nuclear, atomic, plasma and radiation physics and the properties of matter under extreme conditions of temperature and pressure; for defense program studies of thermonuclear reactions and nuclear vulnerability and hardening issues in a controlled laboratory environment; and for civilian applications including energy production, fissile fuel production, isotope production, space propulsion and space power generation [2].

To obtain the conditions necessary for fusion, various pulsed drivers have been investigated - lasers (gas, solid state, and free electron lasers), electron and light ion accelerators, and heavy ion (mass 100-200) accelerators. These investigations, together with a program using nuclear explosives to study target characteristics, have yielded an understanding of the requirements for achieving the high gain in ICF needed for useful energy production (energy gains of about 100)[2,3]. To progress further, two types of laser facilities with different operating characteristics are being considered. One is a laboratory microfusion facility having flexible pulse characteristics and an output energy of

10 MJ. This would be used for single-shot experiments to explore target designs, illumination geometries, and optimum drive pulse shape. For this laser versatility rather than efficiency is important. The second facility, a driver for a power reactor, requires a different set of laser characteristics. After the optimized driver conditions have been determined, laser flexibility is not needed but a higher repetition rate and heat dissipation are. In addition, total cost and overall efficiency are prime considerations if ICF is to be competitive with other energy production technologies. Table 1 summarizes the desired characteristics of the two ICF laser facilities.

TABLE 1. Characteristics of laser facilities for laboratory high-gain ICF experiments and for a reactor driver

Characteristics	Laboratory Fusion Driver	Inertial Fusion Reactor Driver
Pulse energy	10 MJ	2-6 MJ
Peak power	1000 TW	200-600 TW
Pulse duration	0.030-100 ns	~10 ns
Pulse shape	flexible; 20:1 contrast	single, fixed
Pulse repetition rate	single shot	several Hz
Wavelength	250-1000 nm	<500 nm, fixed
Efficiency	unimportant (except for cost impact)	≥10%

Many lasers - gas, liquid, and solid-state - have been investigated in the past for ICF applications. Of these, neodymium-doped glass lasers have provided the greatest advances and are the only lasers routinely used to drive compressions of ICF targets. A succession of increasingly more powerful Nd:glass laser facilities have been built worldwide to pursue ICF research [4,5]. These are flexible experimental tools capable of delivering powers of hundreds of TW, power densities in the range up to 10^{20} W/cm², variable pulse shapes and widths from picoseconds to many nanoseconds, wavelengths (with harmonic conversion) from the near-infrared to the ultraviolet, and focal distances from less than one meter to the many meters needed for target chambers sufficient to contain a 1000 MJ yield. There is little question that solid-state lasers can be scaled up in size to satisfy the laboratory microfusion facility requirements in Table 1. The issue becomes one of cost. For an ICF reactor, on the other hand, solid-state lasers have been deemed to be unsuitable because of the inability to meet the heat dissipation and overall efficiency requirements. However, with new design concepts [6] and recent component developments, an ICF reactor driver also appears to be within the current realm of solid-state laser technology.

Below we review briefly some concepts and laser point designs that have been developed recently to meet the needs in Table 1. Improvements in system efficiency and reductions in system costs are of paramount importance. All of the lasers utilize harmonic generation to obtain the shorter wavelengths needed for efficient fusion drivers. Specific laser architectures, pumping sources, and operating parameters impose limitations and requirements on the optical materials. Therefore materials issues are also discussed.

2. Laboratory Microfusion Facility

Nd:Glass Laser

Neodymium glass lasers used for ICF research have generally been built in a master-oscillator power-amplifier (MOPA) configuration in which the beam is expanded after each stage of amplification to keep the fluence below the damage threshold of the various optical components. The largest laser of this type currently operating is the ten-beam 100 kJ Nova laser at the Lawrence Livermore National Laboratory (LLNL) [7]. It is conceivable that a glass laser meeting the requirements in Table 1 could be built following this approach [8]. The cost, however, would probably be unacceptable. This has prompted the search for more efficient methods of storing and extracting energy and for other laser architectures that are more cost effective.

More efficient extraction of stored laser energy can be obtained using higher fluences or, at fixed output fluence, multipass operation. Because the damage threshold increases approximately as the square root of the pulse duration, longer pulses can lead to higher fluences. With greater fractional energy extraction, the saturation characteristics of the gain media must also be considered. For an inhomogeneous material such as a glass, spectral hole burning and reduced extraction efficiency are possible, but it has been shown that this is not a major problem for Nd:glass lasers operating at room temperature [9].

A design for a compact, efficient, multibeam Nd:glass laser (named Athena) has been developed at LLNL. The basic amplifier unit has a multipass Cassegrainian configuration shown in Fig. 1. The amplifying medium consists of a series of eleven Nd:glass plates approximately 30 cm wide, 55 cm long, and 4 cm thick oriented at Brewster's angle with respect to the beam axis and pumped by banks of linear flashlamps along the vertical walls of the amplifier. Energy extraction involves three

Figure 1. Energy extraction geometry (not to scale) for a rectangular-disk Cassegrainian Nd:glass amplifier (from Ref. 10).

passes. In the first preamplifier pass, a 20 J 2.5-cm high, 30-cm wide strip beam is passed through the lower part of the Nd:glass plate and amplified to 430 J. A convex cylindrical mirror then expands the beam in the vertical direction and directs it through the amplifier for the first of two power amplifier passes which increases the beam energy to 4.7 kJ. A final concave cylindrical collimating mirror directs the beam through the amplifier again for a final pass at which point the energy is 11.7 kJ. About 75 percent of the stored energy is extracted.

In the Athena laser a four-by-four array of these units constitutes an amplifier module. The output beam from the module is passed through a spatial filter and relayed to a two-dimensional array of harmonic generator crystals. Assuming an 85% conversion efficiency, this would yield a 150 kJ pulse of third harmonic (0.35 μm) light. With the improved pumping efficiency and amplified spontaneous emission (ASE) suppression of the Athena design, one such beamline would deliver about twice the energy of the Nova laser but, because of the more compact design and fewer different size components, would require only about 1% of the volume. The projected overall efficiency of Athena is almost 2%, a tenfold increase over Nova technology.

Sixty eight of the above beamlines would develop the 10 MJ needed for a laboratory microfusion facility. The point design for the Athena laser is summarized in Table 2 and represents an extension of values obtained either on Nova or from small-scale prototype experiments. Design details and extensive cost considerations are discussed in reference 10.

Table 2. Point design of the Athena Nd:glass laser

Energy at 0.35 μm	10 MJ
Pulse duration	10 ns
Peak fluence	40 J/cm ²
Energy per beam	150 kJ
Number of beams	68
Electrical bank energy	545 MJ
Overall efficiency	1.8%

Ground State Depleted Laser

Conventional flashlamp excited lasers impose constraints on the size and shape of the gain medium and beam extraction geometries. In addition, the stored energy densities are generally only in the order of a few tenths of a J/cm³. An alternative approach to a laboratory microfusion facility involving a significant increase of stored energy density in the gain medium is based on the concept of a ground state depleted (GSD) laser [11]. These are lasers in which an intense, narrowband laser pump depletes the ground state population thereby creating a large fractional population density in a metastable state. For comparison, whereas typical flashlamp-pumped Nd³⁺ gain media have doping densities of $\lesssim 10^{20}$ ions/cm³ and fractional excited-state densities of a few percent, a GSD laser may have much a lower doping density but a fractional excited-state density of >75%. The corresponding stored energy density in the GSD laser gain medium is $\sim 1\text{--}2$ J/cm³.

A ground state depleted laser is pumped by an intense laser source (fluxes of tens of kW/cm^2) in either a transverse or longitudinal geometry and is characterized by a gain element that is optically thick at the wavelength of the pump laser. That is, $N_0 \sigma(\lambda_p) L \gtrsim 3$, where N_0 is the doping density, σ is the absorption cross section at the pump wavelength λ_p and L is the thickness. As an example, for $N_0 = 10^{19}$ ions/ cm^3 and $\sigma(\lambda_p) = 2 \times 10^{-20}$ cm^2 , this requires an L of at least 15 μm . Possible pump sources for GSD lasers that have been considered [11] include tunable solid-state lasers, dye lasers, or laser diode arrays (the last offering the greatest efficiency).

When the pump flux ϕ is greater than the saturation flux, the ground state is progressively depleted of ions. A bleaching wave starting at the surface transverse inward with time at a velocity $v = \lambda_p \phi / hc N_0$. For $N_0 = 10^{18} - 10^{19}$ ions/ cm^3 and a pump intensity of ~ 30 kW/cm^2 , this corresponds to a velocity of $> 10^4 - 10^5$ cm/s . The propagation of the bleaching wave through the gain medium determines the spatial and temporal distribution of the small-signal gain. Achieving a uniform spatial gain profile requires an intense pump source, optical damage being the ultimate intensity limit. The pump pulse duration should also be much less than the upper-laser-level lifetime to reduce losses by fluorescence and amplified spontaneous emission.

The concept of ground state depletion is applicable to many laser ions; rare-earths ions, in particular, offer many possibilities. Since the ground state is depleted, lasing to any terminal level is possible, including the ground state. For levels greater than $2kT$ above the ground state, about 90% of the stored energy can be extracted. Multipass schemes are again favored for the greatest energy extraction.

Lasing of the $^4F_{3/2} \rightarrow ^4I_{9/2}$ transition of Nd^{3+} under depletion pumped conditions has been demonstrated using an yttrium orthosilicate (Y_2SiO_5) crystal excited by a flashlamp-pumped dye laser [12]. Ground state depletion approaching 80% was observed. One of the problems associated with using this transition is preventing oscillation on the higher gain $^4F_{3/2} \rightarrow ^4I_{11/2}$ transition. The addition of another ion that introduces an absorptive loss at this wavelength (such as Sm^{3+}) has been examined [12]. The absorbing species can be added either by codoping or, if the codopant also quenches the $^4F_{3/2}$ state of Nd^{3+} , by use of a segmented laser material.

The above laser-pumped laser approach combines the advantages of the efficiency of flashlamp-pumped laser technology with the high energy storage inherent in the ground state depleted scheme. If suitable pump lasers and storage media can be found, this can potentially lead to a more compact, less costly laboratory microfusion facility.

3. Fusion Reactor Driver

As evident from Table 1, a fusion reactor puts a higher premium on efficiency than does a laboratory microfusion facility. Also, a pulse repetition rate of several Hz is needed. These demands on the laser were previously thought to rule out the use of solid state lasers which usually have neither the overall efficiency nor the ability to dissipate

the heat generated by optical pumping. Improved cooling designs for slab lasers [6] and recent advances in high-power laser diode arrays [13,14], which make possible increased pumping efficiencies with reduced heat load and with high duty factor, suggest that a reactor driver based on solid-state laser technology is feasible.

KRUPKE [15] has described a conceptual design for a solid-state multibeam, multi-megawatt ICF reactor driver. The amplifiers consist of a series of gas-cooled, face-pumped rectangular plates of gain media approximately 30 cm wide by 50 cm long by 2 cm thick. As an explicit example, estimates were made assuming Nd-doped CaF_2 crystals as the lasing medium. This material was chosen because it should be obtainable at reasonable cost in the sizes required and has an adequate thermal shock resistance parameter (this parameter is a measure of the maximum thermal gradient that a material can sustain without mechanical failure). A pump source consisting of a laser diode array having an area of 1300 cm^2 , a pulse duration of 260 μs , a flux of 3.8 kW/cm^2 and an efficiency of ~60% would produce a stored energy density of ~0.5 J/cm^3 at an overall efficiency of 15%. The heat density deposited in the amplifier plates is estimated to be about 1 W/cm^3 . The plates are mounted at Brewster's angle relative to the beamline axis with the large faces cooled by a turbulent subsonic flow of helium gas at a pressure of 2-3 atmospheres. The total input power needed for cooling the solid-state lasing medium is calculated to be only 3% of the electrical input power required to produce the laser output power, thus the penalty for cooling is minimal.

A single-pass amplifier beamline composed of 30 gain elements would produce 25 kJ of $1.06\text{-}\mu\text{m}$ light in a 10-ns pulse. The projected output fluence of 20 J/cm^2 is below measured damage thresholds and, due to the small nonlinear refractive index of the fluoride host, the beam breakup integral is 2.3 radians which should be acceptable. Using a four-by-four array of such amplifier beamlines followed by nonlinear conversion of the radiation to the third harmonic (at 85% efficiency) produces 340 kJ of 350-nm light. At ten pulses per second, the average power is 3.4 MW. Assuming a target gain of ~100, a laser formed from only ten such modules should be sufficient for a gigawatt electric fusion power reactor.

The cost of the above laser is again an issue. The laser appears to be technologically feasible and capable of delivering the required energy and power for a reactor, but it could not be built at reasonable cost based on currently available high-power laser diode arrays. Increased demand and improved production efficiency should, in time, result in long-lived laser diodes at significantly lower prices.

4. Materials Issues

Although designs and technology for solid state lasers meeting the needs for fusion applications exist, gain media with more optimal parameters could significantly improve performance with respect to output, efficiency and cost. The question of optimal properties must of course be tempered by the question of optimal with respect to what proposed laser architectures and available pump sources. Evolutionary, if not revolutionary, advances may occur which would necessitate a re-examination of optical material parameters.

The Athena laser is based on existing state-of-the-art laser technology and hence most materials issues are minor. Commercially available Nd-doped phosphate glasses such as LG-750 and LHG-8 have properties sufficient to meet the point design criteria and can be produced in the form of rectangular plates of the required 30 x 55 x 4 cm dimensions. Since about 12,000 plates are needed, the total glass volume is greater than 70 m³. Continuous or quasi-continuous melting and casting should therefore be developed to reduce the overall production costs. Probably the greatest technical risk in the Athena design is associated with having optical damage thresholds greater than the 40 J/cm² peak fluence specification in Table 2. This is met by bulk materials and bare surfaces, but high reflectance and polarizer coatings could be a problem.

Of the possible pump sources considered for a ground state depleted neodymium laser, a flashlamp-pumped tunable chromium laser is particularly attractive. Many such lasers have been investigated in recent years (see the article by R. Moncorge in these proceedings); presently BeAl₂O₄ (alexandrite) and LiCaAlF₆ [16] are the most efficient host materials. Although many Nd³⁺-doped crystals and glasses has been considered as the storage medium, the absorption cross sections for Cr³⁺ laser pumping are only marginally adequate and a longer lifetime for the upper laser level is desired to reduce losses due to amplified spontaneous emission.

The ground state depleted concept is also applicable to other lasing ions that may ultimately prove to be more attractive. One possible example is trivalent ytterbium lasing on a transition to a high-lying Stark level of the ²F_{7/2} ground state. Pumping could be either directly into the ²F_{5/2} state of Yb³⁺ or by energy transfer from a codopant sensitizer ion or ions.

Discovery of solid-state gain media having longer energy storage lifetimes would also increase the cost effectiveness of a reactor driver based on laser diode pumping. Ions such as Ho³⁺, Er³⁺, and Tm³⁺ have metastable states with lifetimes in the 5-10 ms range and can be pumped by diode lasers. The lasing wavelengths are in the near-infrared and thus would require shifting to the fourth harmonic to achieve a final laser output at wavelengths <500 nm.

A large number of rare earth and other transition metal ions have now been reported to lase in solids [17]. The physics and properties of rare-earth lasers are particularly well understood [18], hence reliable predictions of laser operation can usually be made from spectroscopic data. In addition, systematic studies of the stimulated emission cross sections of rare earths in a large variety of glasses [19] and crystals show how they can be tailored, within limits, by changes in the chemical composition of the host.

For high-power solid-state lasers, beam breakup due to self focusing and damage to optical components impose critical limits on the operating fluences. Based on measurements of the nonlinear refractive index in a wide variety of crystals and glasses [20], reliable empirical guidelines now exist for estimating the values of the nonlinear index n_2 from the linear index and dispersion. Unfortunately our understanding and ability to predict damage thresholds at a particular wavelength for a given material are much more uncertain, yet damage thresholds determine the fluences that can be used and, in turn, the laser operating efficiencies.

As illustrated in Fig. 2, the laser materials scientist must keep many things in mind when selecting the optimum materials for fusion lasers. Simple figures of merit are usually not sufficient. The issues shown in the figure are also not necessarily all that are important for an overall laser system. For example, thermal and mechanical properties are not included, nor is cost - an increasingly imperative consideration. Note that only the right side of the brain is shown in Fig. 2. This hemisphere produces imaginative thinking, looks at the whole, and provides all-at-one processing appropriate for a multiparameter space. The left hemisphere of the brain produces linear, sequential thinking and one-at-a-time processing appropriate for engineering detail and cost analysis. The workings of both hemispheres and contributions from many individuals will be necessary if the search for solid-state fusion lasers is to be successful.

Figure 2. Several of the properties that must be considered in selecting materials for high-power solid-state lasers for fusion applications

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