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Physics of Laser Fusion

Volume IV

The Future Development of High-Power Solid-State Laser Systems

J. L. Emmett, W. F. Krupke, and J. B. Trenholme

November 1982

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The Future Development of High-Power Solid State Laser Systems

Abstract

Solid state lasers, particularly neodymium glass systems, have undergone intensive development during the last decade. In this paper, we review solid state laser technology in the context of high-peak-power systems for inertial confinement fusion. Specifically addressed are five major factors: efficiency, wavelength flexibility, average power, system complexity, and cost; these factors today limit broader application of the technology. We conclude that each of these factors can be greatly improved within current fundamental physical limits. We further conclude that the systematic development of new solid state laser media, both vitreous and crystalline, should ultimately permit the development of wavelength-flexible, very high average power systems with overall efficiencies in the range of 10 to 20%.

Introduction

Neodymium-doped glass (Nd:glass) was first demonstrated as a laser medium by Snitzer¹ in 1961. Since that time, the Nd:glass laser has been the subject of intensive study and large-system development shared only by two other laser media: CO₂ and DF. The overall international commitment to the development and installation of large Nd:glass laser systems today exceeds \$500 million. Indeed, Nd:glass laser systems have become the worldwide system of choice for laser fusion research.

In the 1960s, the development of relatively large high-energy, short-pulse systems was pursued actively in the USSR, France, and the USA. Perhaps the most successful system developments were accomplished in France by the Compagnie Générale d'Electricité for the Commissariat à l'Energie Atomique, which resulted in the VD series² of lasers with apertures of 64 mm that were ultimately scaled to 120 mm. In the mid-1970s, the center of gravity of large-system development shifted to the USA³⁻⁵ and the USSR.^{6,7}

The choice of Nd:glass as the gain medium resulted primarily from three key factors: its ability to store energy at high density; its ability to propagate high-fluence, high-flux beams; and the apparent simplicity of the technology required for a basic amplifier module. However, the construction of even larger solid state systems and their use in a broader array of applications both appear to be limited by five major factors:

- Laser-system efficiency.
- Operating wavelength.
- Average-power capability.
- System complexity.
- System cost.

In this report, we examine each of these limiting factors to determine the closeness of current designs to fundamental physical limits; we also determine methods for reaching optimal operation. Thereafter, we examine directions for the development of new solid state laser media that can result in greatly enhanced performance. Although the context of the discussion that follows is high-peak-power, high-energy laser systems for laser fusion, many of the results and observations have more general application.

1 Laser System Efficiency

Energy Storage

All large solid state laser systems today are designed with xenon flashlamps as the energy pump source. Therefore, we examine first the limiting efficiency of Nd:glass laser systems that use xenon flashlamps, and then conclude with an outline of some more speculative options.

Xenon flashlamps are highly efficient radiators of optical energy. Numerous studies have established⁸⁻¹⁰ that the total radiative efficiency of these devices lies in the range of 70 to 85% over a rather wide range of operating conditions. These high efficiencies render it the most efficient light source known. Figure 1 displays some typical measurements of the total radiative efficiency deduced using the technique of wall-temperature calorimetry.¹⁰

In this work, all of the data presented on flashlamps were taken on 1.5-cm-bore lamps filled to an initial pressure of 300 Torr xenon. Flashlamp data as a function of lamp loading (joules per centimeter of lamp length) were taken with a pulse duration $\tau = 3(LC)^{0.5}$ of 600 μ s. The pulse shape was held close to the critically damped pulse shape, as the damping parameter¹¹ α was held to values between 0.7 and 1.1. Similarly, data presented as a function of pulse duration are for α held close to the value for critical damping.

As can be seen from Fig. 1, the total radiative efficiency is only weakly dependent on lamp loading in this range; it has a value of approximately 78%. Since these data were taken on very long (112 cm) lamps, it is reasonable to conclude that radiative losses to the lamp end and electrode structures do not account for more than a few percent. Thus, a reasonable assumption for an overall radiative efficiency would be 75%.

Another problem is determining how the efficiency in pumping the Nd^{3+} ion varies with lamp loading, because the details of the spectral output of a xenon flashlamp change rather substantially with lamp loading. Figure 2 displays the relative efficiency of exciting an Nd:ED-2 glass fluorescence detector¹⁰; these data show that the relative pumping efficiency varies only slowly with lamp loading. This is a consequence of the fact that, at low lamp loadings, the pumping is primarily through the absorption bands in the near IR. At higher lamp loadings, where a greater fraction of the flashlamp output shifts toward the blue end of the spectrum, the absorption bands in the green and yellow become increasingly effective.

The next question to address is that of the absolute absorption efficiency of the Nd^{3+} ions. This absorption efficiency is strongly dependent on the number of ions per square centimeter through which the pumping radiation must pass. Figure 3 shows the absorption spectrum of ED-2 glass for three values of the total number of ions per square centimeter. One can readily

Fig. 1. Total radiative efficiency of xenon-filled flashlamp. Bore diameter 1.5 cm; fill pressure 300 Torr; pulse duration 600 μ s; lamp length 112 cm. Arrow shows operating point chosen for calculations discussed in text.

Fig. 2. Relative pumping efficiency of ED-2 silicate laser glass as a function of flashlamp loading. Arrow shows operating point chosen for calculations discussed in text.

Fig. 3. Energy fraction absorbed by ED-2 laser glass, as a function of wavelength, for three values of optical depth.

Fig. 4. Fractional energy absorption of xenon flashlamp output emitted in two spectral bands, as a function of optical depth of ED-2 laser glass.

observe that, at low optical depth, the material is fairly transparent, but that, at high optical depth, nearly half the incident radiation in the 0.37- to 0.94- μ m band can be absorbed. Figure 4 demonstrates this more quantitatively. The curves plotted in Fig. 4 are calculated by our VODEP computer code,¹² which models the flashlamp spectral irradiance and convolves it with the ED-2 absorption spectrum. It calculates the flow of energy to the $^4F_{3/2}$ metastable level of the Nd^{3+} ion, but does not account for fluorescence decay from this level. We will consider the effects of the finite lifetime of the $^4F_{3/2}$ level separately. The operating point chosen for the calculation is shown by the arrows in Figs. 1 and 2. The upper curve and the left ordinate in Fig. 4 show the absolute efficiency of Nd^{3+} ions in ED-2 for absorbing radiation over the entire wavelength region of flashlamp output (0.22 to 1.8 μ m). We observe that, at high optical depth, over 40% of the total flashlamp output energy can be absorbed in the neodymium. The upper curve and right ordinate show the fraction of the radiation emitted in the spectral region of the Nd absorption bands (0.37 to 0.94 μ m) that is absorbed by the neodymium. This fraction can easily reach 50 to 60%. In Fig. 4, the lower curve and the left ordinate display the total absorbed energy, multiplied by the quantum defect ratio (wavelength absorbed/1.06 μ m), and divided by the total flashlamp-output energy. This curve thus represents the limiting energy-conversion efficiency of flashlamp radiation to potentially available 1.06- μ m energy. It should be noted (possibly with some surprise) that this limiting efficiency can reach 25%.

To this point, we have not considered the problems of designing Nd:glass amplifiers that use Nd^{3+} ions at large values of the optical depth. The requirements imposed by both optical-damage thresholds and the desirability of uniform output beams imply that the amplifiers of a large system must have rather flat gain profiles across their useful apertures. Figure 5 plots the gain coefficient of a Nd:glass slab pumped on both large flat surfaces with xenon flashlamps. The three curves A, B, and C represent three different optical depths (Nd ion/cm 2) and correspond to the points A, B, and C of Fig. 4. Clearly, if the laser beam to be amplified must propagate normal to the gradient of the deposited pump energy, one is limited to very low optical-depth values in the absorbing medium (2 to 2.5×10^{20} ion/cm 2). Thus, less than 40% of the limiting pumping efficiency can be achieved (refer again to Fig. 4). The data and calculations¹³ on slab amplifiers fully confirm these conclusions. Further confirmation is provided by the data taken on rod amplifiers,¹⁴ which indicate that, even using reflector geometries that focus the flashlamp radiation into the rod, flat radial-gain profiles are not achieved with density-rod-diameter products much greater than 2.5 to 3.0×10^{20} ion/cm 2 .

Fig. 5. Relative population inversion density as a function of position between the two surfaces of a slab of ED-2 glass. Uniform pumping through the slab surfaces is assumed.

The actual shape of the deposition profile of Fig. 5 is somewhat dependent on the type of Nd:glass used. To display this dependence, the peak/average gain coefficient ratios for three glass types have been calculated for the slab geometry and are presented in Fig. 6. In general, the highest peak/average ratios correspond to the phosphate glasses typified by high-induced-emission cross sections and narrow transition-line widths, while lower ratios are typical of silicates, which possess lower induced-emission cross sections and broader transition-line widths.

From the foregoing discussion, two conclusions are immediately obvious. First, high efficiency cannot be achieved without using large optical depths of Nd ions. Second, flat amplifier-gain profiles cannot be achieved at large optical depth without using amplifier geometries for which each ray in the beam undergoes the same integral of the gain coefficient along its path through the amplifier. Fortunately, there are at least three amplifier geometries¹⁵⁻¹⁷ for which these two requirements can be met simultaneously. These amplifier geometries are illustrated conceptually in Figs. 7 to 9. These geometries can, in principle, be scaled to large-area apertures and are limited only by amplified spontaneous-emission losses along their longest dimension in the gain medium.¹⁸ A detailed comparison of the advantages and disadvantages of these geometries is beyond the scope of this report.

Fig. 6. Peak-to-average ratio of gain coefficients for slabs of silicate (ED-2, L-15) and phosphate (LG-750) laser glasses, as a function of optical depth.

Fig. 7. "Zig-Zag" slab amplifier¹⁵ geometry in which slab is pumped through its broad faces, and the extraction beam is bounced between slab faces using total internal reflection.

Fig. 8. "Active Mirror" slab geometry¹⁶ in which slab is pumped through one of its broad faces coated with a film transmitting pump radiation. The extraction beam enters the other broad face, reflects from the coating film, and exits the entry face.

Fig. 9. "Disk Amplifier" geometry¹⁷ in which broad surfaces of a pair of disks are face-pumped. The extraction beam propagates through the disk faces at the Brewster angle.

Table 1. Limiting efficiencies for pumping Nd:glass gain media for three values of optical depth. The maximum pumping efficiency (last column) is the product of the three efficiency factors (columns 1-3).

Optical depth, Nd^{3+} (ion/cm ²)	Flashlamp radiative efficiency	Fraction absorbed in Nd^{3+}	Average quantum efficiency	Maximum pumping efficiency
2×10^{20}	0.75	0.170	0.63	0.080
1×10^{21}	0.75	0.335	0.62	0.156
3×10^{21}	0.75	0.440	0.61	0.200

At this point, it is appropriate to summarize the limiting efficiency of xenon-flashlamp-pumping Nd:glass under our ideal simplifying assumption that all of the radiation passes once through neodymium glass before it is lost. This summary, which explicitly exhibits the dependency on optical depth, is shown in Table 1. Note that the effects of the finite lifetime of the $^4\text{F}_{3/2}$ level have not yet been included. Table 1 clearly demonstrates that the limiting pump-energy efficiency, from electrical energy supplied to the flashlamps to available 1.06- μm photons, is approximately 20%.

We next consider the means by which this limiting efficiency might be increased. To do this, it is necessary to quantitatively determine the location in wavelength space of the 40 to 50% of the flashlamp radiant output not absorbed by the neodymium. Figure 10 shows the distribution of energy emitted by the xenon flashlamp in three spectral ranges: first, the energy at wavelengths shorter than 0.37 μm ; second, the energy at wavelengths between 0.37 and 0.94 μm , which passes through the glass without being absorbed; and third, the energy at wavelengths longer than 0.94 μm , which cannot pump the upper laser level of Nd^{3+} . The data shown in Fig. 10 are somewhat approximate, because really sharp cutoff filters to take the data were unavailable. However, we may conclude that, at the operating point shown in Figs. 1 and 2, approximately 16 to 18% of the energy radiated by the lamp is at wavelengths longer than 0.94 μm , while about 16% of the energy is at wavelengths shorter than 0.37 μm . Note that, as the lamp loading increases, the UV fraction increases while the IR fraction decreases (as expected). Also shown in Fig. 10 is the fraction of the flashlamp output in the 0.37- to 0.94- μm band that is not absorbed by the Nd for the three optical depths shown in Figs. 3 to 6.

In principle, it should be possible to capture the "unused" radiation in these three spectral regions and use it to increase the limiting pump-energy efficiency. Two types of converters are candidates for this purpose: energy converters and quantum converters. The energy converters are probably the less generally recognized and are discussed first.

Fig. 10. Fractions of flashlamp energy emitted in two bands: $\lambda < 0.37 \mu\text{m}$ and $\lambda > 0.94 \mu\text{m}$, as a function of lamp loading. Fraction of flashlamp energy emitted in the $0.37 \leq \lambda \leq 0.94 \mu\text{m}$ band which is not absorbed by ED-2 Nd:glass with three different optical depths.

Fig. 11. Schematic showing the flow of electrical and optical energy in a xenon flashlamp.

As Fig. 1 indicates, the flashlamp itself is a very efficient converter of electrical energy to optical energy. Under the operating conditions noted, the plasma is in local thermodynamic equilibrium throughout most of the discharge period. Thus, with the exception of the physical location of the energy deposition within the volume of the plasma, absorbed optical energy will heat the emitting/absorbing xenon plasma, with effects equivalent to electrical-energy deposition. While this fact has been implicitly or explicitly realized by many researchers in the field,¹⁹ only in the USSR have detailed experimental and theoretical studies of the process been carried out.²⁰ These studies strongly indicate that the flashlamp can be used as an energy converter and that the only significant difference between electrical heating and optical heating is the resulting plasma-temperature profile. Thus, it is probably correct to assume that absorbed optical radiation will be converted to emitted optical radiation with close to the same overall efficiency with which deposited electrical energy is converted to optical radiation. To see how such a process might work, refer to the energy flow diagram in Fig. 11. By equating the total energy input (optical + electrical) to the total energy output, we can easily show that the ratio of the pump efficiency with optical feedback to the efficiency without feedback is just

$$\frac{\eta_{\text{feedback}}}{\eta} = \frac{1}{1 - \epsilon p} \quad (1)$$

where ϵ is the flashlamp radiative efficiency and p is the fraction of total flashlamp radiative output reabsorbed back into the flashlamp plasma. To simplify the remainder of the discussion and to extend its technical validity, we assume that all optical input to the flashlamp allows a corresponding reduction of electrical input, so that the flashlamp operating point remains approximately constant.

The data in Table 1 can be combined with the data in Fig. 10 and Eq. (1) to yield the limiting pump-energy efficiencies in Table 2. In Table 2, the effect of feedback is applied to each spectral region separately, along with the limiting result for feedback of all energy not absorbed by the Nd ions.

The practical implementation of optical feedback is by no means trivial. Conserving photons rigorously is required to ensure that the only energy sinks are the Nd ions and the flashlamp inefficiency (i.e., wall losses). This is a substantially more difficult task than the realization of low-loss resonators for a laser. The difficulty is greater because a pumping cavity must be developed that has low-loss over an extremely wide wavelength interval, as well as

Table 2. Limiting pumping efficiencies for Nd:glass with optical feedback and flashlamp energy conversion.

Optical depth, Nd ³⁺ (ion/cm ²)	Limiting efficiency no optical feedback	Efficiency with optical feedback			All λ s not absorbed by Nd ions
		Only $\lambda < 0.37 \mu\text{m}$	Only $0.37 < \lambda < 0.94 \mu\text{m}$	Only $\lambda > 0.94 \mu\text{m}$	
2×10^{20}	0.080	0.091	0.133	0.092	0.226
1×10^{21}	0.156	0.177	0.217	0.179	0.332
3×10^{21}	0.200	0.227	0.250	0.230	0.362

over all angles of incidence from 0 to 90°. In contrast, a laser resonator usually needs to be low-loss only over a narrow wavelength interval and at one angle of incidence. The problem of a low-loss pump cavity is further complicated by the necessity of propagating the laser beam in and out of it, while not allowing the pump energy to escape out the same ports. This latter situation implies that amplifiers must have large length-to-diameter ratios to minimize the solid angle of the input and output ports, as seen from the pump sources.

The first step in designing an efficient cavity is to use reentrant-type reflectors on each flashlamp.²¹ Proper design can ensure that all output radiation of the flashlamp will pass at least once through the Nd:glass before it can be reabsorbed by another flashlamp. The conventional close-spaced flashlamp arrays with closely coupled reflectors suffer pump-efficiency degradations of 25 to 35% just from the reabsorption of emitted light by flashlamp plasma before it reaches the laser medium. The reentrant reflector arrays are illustrated conceptually in Figs. 7 to 9. Taking the three bands in order of increasing wavelength, we note that feedback of the energy at $\lambda \leq 0.37 \mu\text{m}$ must occur before it impinges on the Nd:glass, because all Nd:glass types (with the exception of Nd:SiO₂) begin to absorb strongly in the 0.34- to 0.37- μm region. There are two basic approaches to feedback in this region: first, the flashlamp array could be surrounded by a wavelength selective reflector; second, a UV wide-angle reflective coating could be applied directly to the flashlamp.²² This latter approach deserves more careful study and appropriate materials development. Feedback of the unabsorbed radiation in the interval $0.37 \leq \lambda \leq 0.94 \mu\text{m}$ can be achieved only by a very highly reflective pump cavity with little area taken up by holes or other "black" regions for pump photons. In the wavelength region $\lambda \geq 0.94 \mu\text{m}$, either approach proposed for the other two bands could be employed. It might be noted that IR coatings on lamp envelopes to improve efficiency are common on lower-power light sources.²³ Since major leverage exists for recirculation of photons at all wavelengths longer than 0.37 μm , it is natural to investigate the reflective properties of some conventional materials. In Fig. 12, the reflectivities are indicated for freshly evaporated silver and aluminum, as well as for the diffuse reflector BaSO₄.²⁴⁻²⁶ Plotted are the single- and four-bounce reflectivities. From examination of these plots, it is clear that conserving photons will be difficult where multiple passes through the cavity are required. However, the efficiency improvements from even partial success are quite significant. Up until the present time, little effort has been expended to optimize the efficiency of Nd:glass lasers with optical feedback. Thus, it is unclear what fraction of the limiting efficiencies of Table 2 might actually be achieved.

Next, we consider the two types of quantum converters: intrinsic and extrinsic.

Intrinsic Quantum Converters

An intrinsic quantum converter is no more than a sensitizing ion co-doped with Nd ions in the glass medium. It exhibits absorption in regions omitted by the Nd ions, and it is capable of

Fig. 12. Spectral reflectivities of freshly evaporated silver, aluminum, and barium sulfate, for one and four bounces.

Fig. 13. Spectral absorption of Cr:glass (phosphate; optical depth is 2×10^{19} ion/cm²) and Nd:ED-2 glass (optical depth is 10^{21} ion/cm²).

transferring a significant portion of this energy to the Nd ions. A number of sensitizing ions have been studied in relation to Nd:glass lasers.²⁷⁻³⁰ One of these, trivalent chromium (Cr^{3+}), has proved to be by far the most effective sensitizer, particularly in the low-quenching phosphate glasses studied extensively in the USSR in recent years.^{27,31,32} This method of increasing the efficiency of Nd:glass lasers is constrained by several factors that can be understood by referring to the spectra shown in Fig. 13.

In glass, Cr^{3+} ions absorb radiation in the broad blue and red absorption bands and emit excitation energy in the Stokes band peaked near 900 nm. At room temperature, the emission is quenched. Quantum efficiencies of less than 10% and fluorescence lifetimes of 20 to 30 μs are common.^{27,32,33} Thus, for energy absorbed by Cr^{3+} ions to be efficiently transferred to the Nd^{3+} ions, the transfer rate must greatly exceed the nonradiative and spontaneous decay rates of the Cr^{3+} ions. Transfer rates in the range of 10^5 to 10^6 per second are required. To attain such rates, the Nd^{3+} ion density must be greater than 5×10^{20} ion/cm³. However, since Nd ion-ion quenching occurs in this density range, a balance must be struck, and the transfer efficiency will generally be less than unity.³¹ Because of this, it is important to note in Fig. 13 that the absorption bands of Cr^{3+} ions partially overlap those of the Nd^{3+} ions. Since the transfer efficiency will be less than unity, it is clear that all the radiation not directly absorbed by Nd ions cannot be utilized by this quantum converter technique and that the improvement in efficiency will depend directly on the size and doping level of the gain medium.

It has been predicted³¹ that the excitation efficiency of small (a few millimeters) La-Li phosphate-glass lasers can be increased by 45% upon incorporation of a few tenths of a mol-percent chromium. For an optically thick Nd:glass disk, 4 cm thick, containing 5×10^{20} ion/cm³ Nd and 5×10^{18} ion/cm³ Cr, we estimate a 10% improvement in energy conversion efficiency, from 23% to 25% (potentially available 1.0 eV photon energy divided by flashlamp output energy). In the case of Nd^{3+} ions in crystals, with characteristically narrower absorption transitions compared to glass, we would expect a considerably larger pump-efficiency improvement.³⁴

Extrinsic Quantum Converters

We define an extrinsic quantum converter as a material external to the Nd:glass medium; it is a material doped with an ion or molecule that absorbs in a region not matching Nd-ion absorption bands, and that emits fluorescence that matches Nd-ion bands.

Fluorescent converter T_r = Pump cavity transfer efficiency	(a) Xenon	(b) Xenon	(c) Xenon	(d) Nd disk Xe	(e) Nd disk Xe
Refractive index n of converter	1.5	1.5	1.45	$\leq n$ (Nd:glass)	$\leq n$ (Nd:glass)
Fraction of converted radiation available for absorption in Nd	$0.13 T_r$	$0.18 T_r$	$0.21 T_r$	$0.87 T_r$ (UV) (for $n = 1.5$)	$1.0 T_r$ (for $n = 1.5$)

Fig. 14. Five basic optical geometries for the placement of quantum converters (schematic).

Two primary problems are associated with the use of fluorescent converters to enhance the pumping of a laser medium. One problem concerns the placement of the converter in some geometrical optical relation with the laser medium to assure efficient transport of converted radiation to the laser medium. Figure 14 illustrates five potential placements of a fluorescent converter. For each of these, we show the maximum efficiency with which converted radiation can be coupled to the laser medium. In Fig. 14(a), geometry is the well-known luminescent solar concentrator, which will emit only 13% of the converted energy from one side in the direction of the laser medium; the radiation from the other side will be reabsorbed in the flashlamp. Most of the reemitted energy will be trapped in the converter and will ultimately be dissipated in "black" regions at the edges of the converter sheet. The geometries of Figs. 14(b) and (c) introduce curvature in the plate of geometry (a) in an attempt to increase the output coupling. While this is partially successful, achieving output couplings greater than 20% is difficult. Determining the overall converter efficiency requires this output-coupling factor to be multiplied by the spectral overlap of the converter absorption and the flashlamp emission, the quantum efficiency of fluorescence, the spectral overlap of converter emission and Nd absorption, and, finally, the cavity-transfer efficiency, T_r . As a result, it is clear that geometries (a), (b), and (c) should probably be abandoned.

In the opinion of the authors, the only remaining way to use these geometries is to incorporate a bulk scatterer in the fluorescent medium, which might couple out the fluorescent radiation while not proving too lossy for directly transmitted flashlamp radiation. This possibility deserves some careful analytical and experimental work before final conclusions are drawn.

The geometries shown in Figs. 14(d) and 14(e), where the converter medium is in optical contact with the laser medium, offer excellent coupling efficiencies and, thus, possess a significant chance of success. Geometry (d) is appropriate to the conversion of the short-wavelength radiation; however, it requires pump-cavity reflectors that have excellent reflectivity in the UV portion of the spectrum. Geometry (e) is appropriate for conversion of the long-wavelength radiation flowing between the Nd pump bands.

Figures 15 to 17 show the "ideal" absorption and emission bands of short-wavelength and long-wavelength quantum converters (solid lines), respectively, together with the excitation and emission spectra of some suggested converter media (dotted lines). Effective short-wavelength converters may be formed either by a coumarin dye dispersed in a plastic host³⁵, or by divalent europium ions dispersed either in a phosphor powder³⁶ or in silica glass.³⁷ Figure 15 shows the

Fig. 15. "Ideal" absorption and emission features for a short-wavelength quantum converter (solid lines). Excitation and emission spectra³⁵ of coumarin dye 522 in DMSO (dotted lines).

Fig. 16. "Ideal" absorption and emission features for a short-wavelength quantum converter (solid lines). Excitation and emission spectra of $\text{CaCa}_{0.95}\text{Eu}_{0.05}\text{F}_3$ phosphor (Ref. 36) (dotted lines).

Fig. 17. "Ideal" absorption and emission features of long-wavelength quantum converter (solid lines). Absorption and emission spectra (Ref. 38) of $\text{Cr}^{3+}:\text{GdScGa-Garnet}$ (dotted lines).

absorption and emission spectra of coumarin dye 522 in dimethylsulfoxide, in relation to the "ideal" converter spectra. This dye is characterized by a large Stokes shift, a quantum efficiency of 80%, and high photostability.³⁵ As shown in Fig. 16, Eu^{2+} ions in the phosphor cited absorb radiation below 450 nm and fluoresce in a band centered near 500 nm with a quantum efficiency of about 70% and a lifetime of a few microseconds. The long-wave converter might be formed by an oxazine-type dye in plastic; alternatively, it might be formed by a chromium-doped cubic phosphor dispersed in a transparent index-matched plastic film. Such a phosphor might be $\text{Cr}^{3+}:\text{GdScGa-garnet}$ ³⁸ with the absorption and emission spectra shown in Fig. 17. This crystallite exhibits³⁸ a nominal unity quantum efficiency and a fluorescence lifetime of 120 μs . We estimate that use of an optimized "short-wave" quantum converter could increase the energy fraction of potentially available 1.06- μm photons from 23% (Nd only) to 27% (Nd plus short-wave converter), and we estimate that the additional use of a "long-wave" converter would increase this fraction to 31%.

Thus far, we have discussed only the transfer efficiency from electrical-energy input to the pump source to potentially available 1.06- μm energy. The effects of radiative and nonradiative

decay of excitation from the ${}^4F_{3/2}$ level during the pump pulse have not been included. Assuming that the fluorescent decay from this state is truly exponential, the relationship of the population, n^* , in the ${}^4F_{3/2}$ to the pump rate is simply

$$\frac{dn^*}{dt} = -\frac{n^*}{\tau} + P(t) \quad (2)$$

where τ is the fluorescent lifetime and $P(t)$ is the input pump rate. If $P(t)$ is represented as a half-period sine wave of unit area (which is close to the shape of a critically damped electrical pulse into a flashlamp), the solution of Eq. 2 for the peak value of n^* is shown in Fig. 18. Also shown in Fig. 18 are actual data of the peak fluorescence from a Nd:glass fluorescent detector for constant flashlamp input energy and various pulse widths. These data, which have been normalized by the overall radiative efficiency of the flashlamp, correspond closely to the calculations, except for the shorter pulses. For the latter, the finite time required for the full hydrodynamic development of the discharge results in much higher actual plasma-power densities per unit of plasma volume than the values averaged over the bore volume. Thus, the efficiency for pumping Nd begins to fall rapidly. For materials with fluorescent decay times in the 250- to 300- μ s regime, a peak-stored energy fraction of 0.5 of the energy input to the ${}^4F_{3/2}$ level is all that is attainable. To increase these levels will require longer-fluorescent-lifetime materials or development of improved flashlamps for short-pulse operation. Given some development, peak-stored-energy fractions of 0.5 to 0.7 are probably attainable. It is appropriate to note here that most neodymium-containing glasses exhibit a nonexponential decay. Thus, an "effective" decay time, in the sense of Eq. (2), is in general shorter than the first e -folding decay time. To maximize overall efficiency, large optical depths and minimal nonradiative relaxation of the ${}^4F_{3/2}$ state are clearly important. In this context, the recent development of phosphate laser glasses with very low OH^- content and minimal Nd-Nd quenching is particularly important.^{39,40} Table 3 summarizes the overall energy-storage efficiency that can be achieved in the presence of fluorescent decay. Three cases are presented. The first case is the limiting efficiency with no optical feedback to the flashlamp and no fluorescent converters. Even in this case,

Fig. 18. Fraction of the pump energy remaining in the ${}^4F_{3/2}$ level, at its maximum value, as a function of pump pulse width (in units of the decay time). Dots show experimental values for ED-2 Nd:glass with 3 wt% Nd_2O_3 .

Table 3. Summary of limiting energy storage efficiencies of Nd:glass with fluorescence decay.

Optical depth, Nd ³⁺ (ion/cm ²)	Overall energy storage efficiency with fluorescent decay (Peak stored fraction 0.4-0.7)		
	Limiting efficiency without energy feedback or quantum converters	Limiting efficiency with complete energy feedback	Limiting efficiency with optimal use of quantum converters and IR feedback
2×10^{20}	0.032-0.056	0.09-0.16	—
1×10^{21}	0.062-0.110	0.13-0.23	0.10-0.17
3×10^{21}	0.06-0.14	0.15-0.25	—

careful design should yield efficiencies in the 6 to 12% range. The next two cases present the limiting results for full optical feedback and for optimal use of fluorescent converters and IR feedback. It is clear that, if the technology can be developed to allow effective implementation of these techniques for efficiency enhancement, then peak storage efficiencies of up to 25% might be attainable.

Energy Extraction

Having discussed at length the range of efficiencies with which energy may be stored in Nd:glass, we now turn to the efficiency of extraction. The extraction efficiency is determined by five major factors, which are addressed in order below:

- Saturation properties of the laser medium.
- Nonlinear optical propagation effects.
- Damage threshold of the laser medium.
- The overall transmission loss of the amplifier
- The ratio of the laser-beam area to the pumped area of the amplifier (fill factor).

The energy deposition into the amplifying medium is simply determined by measuring the fraction of the energy output of the flashlamp that is absorbed in the Nd pump bands. The energy available at 1.06 μm is then determined as previously described. An average induced-emission cross section, σ , then relates the measured gain coefficient to the population density (or stored energy density) in the $^4\text{F}_{3/2}$ state. The average induced-emission cross section is determined by applying a theoretical framework, developed by Judd⁴¹ and Ofelt,⁴² for calculating the electric dipole transition probabilities between pairs of energy levels of the 4f ground configuration of trivalent rare-earth ions in terms of the perturbing effects of the odd-symmetry crystal fields at the rare-earth ion site. This formalism allows the transition probabilities between pairs of states to be calculated from three phenomenological parameters, which are determined by fitting to simple integrated absorption-intensity measurements. The transition probabilities, coupled with the measured linewidths, allow a determination of σ . This theoretical formalism, originally developed for crystals with a single rare-earth ion site, was extended by Krupke⁴³ to the case of glassy materials, where a distribution of sites exists. This formalism can thus be used to determine an average σ for Nd:glass. In conducting an amplifier energy-extraction experiment, we measure the small-signal-gain coefficient, the input fluence, and the output fluence. The application of the Frantz-Nodvik equation,⁴⁴

$$\phi_{\text{out}} = \phi_s \ln [1 + G(e^{\phi/\phi_s} - 1)] \quad , \quad (3)$$

where ϕ_s is defined as the saturation fluence, ϕ_{out} is the output fluence, ϕ is the fluence in the medium, and G is the small-signal gain of the amplifier, allows the determination of the saturation fluence, ϕ_s . In general, we find a value of $\phi_s \leq h\nu/\sigma$, where ν is the frequency of the optical radiation. This result can be interpreted as being due to a linear superposition of individual oscillators at various sites that do not all have the same homogeneous linewidth or line position. Thus, the individual sites that have their peak cross section at the extracting wavelength will saturate easily, while those for which the extracting wavelength lies in the wings of the line will exhibit a much higher saturation fluence. The saturation characteristics of various Nd:glass compositions vary widely, which is somewhat surprising. Two examples⁴⁵ of this behavior are shown in Fig. 19. To effectively extract the stored energy, it is necessary to achieve operation under conditions where $\phi_s \geq h\nu/\sigma$. Measurements on ED-2 silicate glass, shown in Fig. 19(a), imply that energy extraction defined by the Frantz-Nodvik equation will not be achieved until output fluences are well beyond $1.5 h\nu/\sigma$. In contrast, however, is the case of LG-750 phosphate glass, shown in Fig. 19(b), where the saturation/energy extraction behavior is only weakly dependent on the extraction fluence. With this latter material, over 90% of the stored energy is accessible by extracting in the range of 1 to $2 h\nu/\sigma$. In conclusion, it is clear that efficient extraction of the stored energy at a given number of saturation fluences is critically dependent on the type of glass chosen. However, it is expected (though not yet demonstrated) that, at very high

Fig. 19. Saturation behavior (Ref. 45) of Nd:glass. (a) ED-2 silicate glass, (b) LG-750 phosphate glass. Saturation fluence ϕ_s is plotted as a function of output fluence ϕ_{out} , both normalized to the quantity $h\nu/\sigma$, where ν is the laser frequency and σ is the effective stimulated emission cross section. Best-fit linear functions represent all ED-2 data and the LG-750 data that were measured with 20-ns pulses. Cross sections used for normalization are $\sigma = 2.7 \times 10^{-20} \text{ cm}^2$ for ED-2, and $\sigma = 4.0 \times 10^{-20} \text{ cm}^2$ for LG-750.

extraction fluences (i.e., several times $h\nu/\sigma$), ϕ_s will approach $1.0 h\nu/\sigma$. Appendix A discusses the saturation measurements and presents additional data.

The energy-extraction efficiency of amplifiers is also limited in the short pulse regime by nonlinear propagation effects first described by Bospalov and Talanov⁴⁶ and quantitatively demonstrated by Bliss et al.⁴⁷ In essence, amplitude ripples existing on the laser beam caused by diffraction (or by inhomogeneities in the laser medium or ancilliary optics) grow exponentially and eventually render the beam unfocusable. The spatial frequency with the largest growth rate^{47,48} grows as

$$l = l_0 e^{2B} \quad (4)$$

The factor B is called "the breakup integral" and is

$$B = \frac{8\pi^2 \times 10^7}{\lambda_v c} \int_0^L (n_2/n_0) I d\ell \quad (5)$$

where n_2 is in electrostatic units, I is in watts per square centimeter, ℓ is the path length through the medium in centimeters, and n_0 is the normal refractive index at the vacuum wavelength, λ_v . Detailed experiments have shown that values of B of 2.0 to 3.0 radians between spatial filters can be tolerated with current levels of amplitude noise on large laser beams.⁴⁹ The constraint of $\Delta B \leq 3.0$ limits the fluence of very short pulses to be below that necessary for efficient energy extraction.

Another major limitation on the extraction efficiency is the damage threshold of the laser medium itself. A summary of damage data⁵⁰⁻⁶⁰ is provided in Fig. 20. Shown on this graph are bulk-damage thresholds for glasses and crystals as well as surface-damage thresholds for glasses. Clearly, the damage-fluence limitation is due to surface rather than bulk damage. In actual fact, the bulk-damage thresholds may be much higher than those shown, given the substantial

Fig. 20. Bulk and surface damage thresholds of optical materials as a function of pulse duration. Measurements made at wavelengths of 1.06 or 0.69 μm . Shaded bands correspond to threshold fluences increasing as the square root of pulse duration. (Data: Refs. 50 to 60).

difficulty of separating self-focusing effects from true bulk damage. Today, the state of the art of surface preparation provides surface-damage thresholds that can be characterized by

$$E_{th} (J/cm^2) \leq 10 \sqrt{\tau(ns)} \quad (6)$$

where the pulse duration, τ , is measured in nanoseconds. The damage thresholds of the surface of the laser medium can provide another limitation on the overall extraction. This limitation becomes important with the low-induced-emission cross section ($\sigma \approx 1 \times 10^{-20} \text{ cm}^2$), wide-line silicate glasses. It is far less constraining on the high-cross-section, narrow-line phosphate glasses.

In addition to the above factors, the passive nonsaturable linear loss in the laser medium and at the surfaces also provides an extraction-efficiency limitation. All the factors discussed above have been combined into Fig. 21 to illustrate the effects. For systems designed to operate in the subnanosecond regime, overall extraction efficiencies will be limited to the 5 to 25% range by the nonlinear propagation effects. At slightly longer pulses, the damage threshold provides the major limitation. The limiting extraction efficiency is determined by the nonsaturable linear-loss coefficient, γ . In Fig. 21, the limiting extraction efficiency is determined by the choice of an overall γ of 0.0025 cm^{-1} . At $\gamma = 0.001 \text{ cm}^{-1}$, the limiting extraction efficiency is approximately 87%. The dependence of the results of Fig. 21 on glass type, stored energy density, and loss coefficient is presented in Appendix B. It can be easily concluded that the efficiency of Nd:glass laser systems designed for operation in the 5- to 25-ns regime will be much greater than for those designed for nanosecond or subnanosecond operation.

Up to this point, we have considered the entire pumped volume of the laser medium to be uniformly illuminated by a plane-wave extraction beam. In real systems, this is not possible because of diffraction-induced amplitude modulation on the beam caused by the sharp edges of the amplifier. If a Gaussian spatial shape is propagated through the amplifier, the hard aperture must not intercept the beam at more than e^{-3} of the central intensity. This limits the effective volume utilization, or filling factor to about 40%. The employment of an image-relay system⁶¹ throughout the whole laser system allows much more rectangular spatial profiles to be propagated, resulting in filling factors of 70 to 80%. This technique is currently in use in all systems of modern design.

In conclusion, the limiting extraction efficiency is the product of both the medium extraction efficiency shown in Fig. 21 and the filling factor. Thus, overall amplifier extraction efficiencies of 50 to 60% are achievable for pulse durations of several nanoseconds or longer.

Fig. 21. Calculated extraction efficiency of a single-pass Frantz-Nodvik amplifier as a function of extraction pulse duration for amplifier gains of 3, 10, and 30.

2 Wavelength Flexibility

In inertial confinement fusion research, the trend in recent years has been to shorter and shorter wavelengths. This shift is driven by the combination of improved absorption of the light in the plasma, a substantial reduction in the production of hot and superhot electrons, and an increase in the production efficiency of thermal x rays⁶²⁻⁶⁴ exhibited for irradiation wavelengths shorter than 1 μm . Harmonic conversion of existing Nd:glass laser systems has proven to be a low-cost, efficient way of providing the shorter-wavelength radiation.

Harmonic generation was first demonstrated by Franken et al.⁶⁵ shortly after the development of the ruby laser. Giordmaine⁶⁶ demonstrated how to make the process efficient with the clever technique of phase matching in birefringent crystals. Subsequently, extremely high harmonic-conversion efficiencies (50 to 90%) have been demonstrated for conversion of intense beams ($I \geq 1 \text{ GW}/\text{cm}^2$) to the second, third, and fourth harmonics⁶⁷⁻⁶⁹ using KH_2PO_4 (KDP) and its crystal isomorphs. In this section, we will comment on some of the more unconventional approaches to harmonic generation for large Nd:glass systems.

Figure 22 shows the crystal orientation for Type II harmonic generation in KDP at 1.053 μm . Both the 1ω input and 2ω outputs are linearly polarized. Figure 23 shows the calculated plane-wave conversion efficiency for a 1.8-cm-thick crystal as a function of input intensity for three values of the input beam divergence, $\Delta\theta$. As can be seen, conversion efficiencies exceeding 80% can only be achieved for a very limited range of intensities or for high-quality input beams ($\Delta\theta < 100 \mu\text{rad}$). In Fig. 24(a), we show the quadrature⁷⁰ approach to second-harmonic generation. Both crystals are cut for Type II phase matching; however, the optical axes are arranged so that the planes containing the laser-beam propagation vector and the crystal optical axes are orthogonal. The incident fundamental plane wave is polarized at 45° to the kz plane of both crystals, which allows phase matching for both. The second-harmonic waves generated in both crystals are orthogonal, so the conversion efficiencies are independent of each other. The overall output is thus the simple sum of the output from each crystal. The conversion efficiency is then just

$$\eta = \eta_1 + \eta_2(1 - \eta_1) \quad (7)$$

The great advantage of the quadrature scheme is that it allows efficient harmonic generation over an extremely wide intensity range. This results particularly if the crystals are of two quite different thicknesses, so that the thin crystal can convert the higher intensities and the thick crystal can convert the lower intensities. Figure 25 shows the conversion efficiency for the

Fig. 22. Crystal and electric vector orientations for Type-II harmonic generation in KDP. Extraordinary axis, e; ordinary axis, o.

Fig. 23. Calculated plane-wave second-harmonic conversion efficiency as a function of the fundamental beam intensity, for KDP crystal 1.8 cm long and for three different values of beam divergence, $\Delta\theta$.

Fig. 24. Crystal and electric vector orientations (a) for "quadrature" second harmonic generation; and (b) for cascade third harmonic generation; extraordinary axis, e; ordinary axis, o.

Fig. 25. Calculated plane-wave second-harmonic conversion efficiency for quadrature scheme as a function of fundamental beam intensity and for three different values of beam divergence, $\Delta\theta$. KDP crystals assumed with $L_1 = 1.2$ cm, $L_2 = 0.6$ cm, and $L_1 + L_2 = 1.8$ cm.

quadrature scheme with a total crystal length ($L_1 + L_2$) equal to the crystal length of Fig. 23 (1.8 cm). As can be clearly observed, efficient harmonic conversion is achieved by the quadrature scheme for both a wider range of intensities and higher-beam-divergence input beams. The wide intensity range of efficient conversion is particularly valuable for use in systems that must generate a wide variety of pulse widths or complex pulse shapes. The only liabilities incurred for this flexibility are slightly increased mechanical complexity and an output beam polarization that is elliptical and changes with intensity.

The quadrature system in KDP has another interesting feature, as shown in Fig. 24(b). The two crystals are also in the basic orientation for Type II-Type II third-harmonic generation.^{67,71} Thus, a simple rotation of the crystals by 10° around the beam propagation axis and a tilt of 4.4 mrad to the phase-match angle for $1\omega + 2\omega$ mixing are all that is required for third-harmonic generation. Optimization of the crystal assembly for both second and third-harmonic generation limits the effective conversion range for both, as shown in Fig. 26, but produces a low-cost approach to three-wavelength operation of Nd:glass systems. The SHG-THG system illustrated in Figs. 24 and 26 is being implemented⁷² on the Nova laser system at LLNL.

Fig. 26. Calculated quadrature second-harmonic and cascade third-harmonic efficiencies as a function of fundamental beam intensity for a beam divergence angle $\Delta\theta = 100 \mu\text{rad}$ and for KDP crystals of equal thickness, $L_1 = L_2 = 1.4$ cm.

The Nova-system beam diameter is 74 cm and therefore requires 74-cm-diameter harmonic-conversion crystal assemblies. Fortunately, KDP is rather easily grown from water solutions, and the scale-up of crystal size has proceeded well, as shown in Fig. 27. From the larger of these crystals, we are able to fabricate the 27-cm-square plates shown in Fig. 28. Since the growth of crystals large enough for 74-cm-diam plates would require a prohibitively long time, the decision was made to develop crystal-array technology. A schematic of the crystal array is shown in Fig. 29. The fused-silica output window is necessitated by the UV solarization of conventional optical glasses at the third harmonic.

The array concept was tested with nine 5-cm-square crystals, shown in Fig. 30. Also shown in Fig. 30 is the output 2ω beam, indicating uniform harmonic-conversion efficiency and little additional distortion from the input beam. The array technology is made possible by extremely precise diamond-point machining and precise measurement of the KDP crystals,⁷³ so that the phase-matching direction and the surface normal are coincident to an accuracy of $\pm 30 \mu\text{rad}$. The diamond-point machining produces such a finely finished surface that no subsequent grinding or polishing is required. The crystal-array technology using the $2\omega/3\omega$ scheme of Fig. 24 is being implemented on Nova at the 74-cm diameter using the 27-cm-square crystal plates shown in Fig. 28.

For the development of future harmonic-generation capabilities at very large apertures, there appear to be several interesting directions to pursue. First, if materials that exhibit 90° phase matching at a convenient temperature (such as deuterated cesium dihydrogen arsenate, CD^*A) could be grown in large sizes, the greatly reduced angular sensitivity would result in greatly reduced fabrication and alignment-system costs. Further in the future, the extremely high nonlinear susceptibilities of many organic materials⁷⁴ encourage us to consider the growth of large oriented films on transparent substrates. Such oriented-growth techniques might also be applied profitably to more conventional materials. Yet another way to achieve nonlinear properties over large areas is the use of liquid crystals, which, with material development, may ultimately prove useful without conventional crystal growth.

Fig. 27. Large crystal of KDP grown by Cleveland Crystals, Inc., Cleveland, Ohio. Crystal measures 30×32 cm in cross section at the base and is 64 cm long.

Fig. 28. Large crystal plates of KDP fabricated using a diamond-point machining technique (Ref. 73).

Fig. 29. Schematic of the harmonic-crystal-array design to be used in the Nova laser system. Input window is made of conventional high-quality glass (BK-10); output window is made of fused-silica.

Fig. 30. Experimental nine-crystal array of 5-cm-square KDP crystals. Representative second-harmonic output beam.

3 Operation at High Average Power

Nd:glass is not usually thought of as a medium for the development of high-average-power laser systems. Indeed, in the form most usually considered—that of large-diameter rods—it is not useful for high average power; the combination of low thermal conductivity with temperature gradients normal to the propagation of an optical beam render high average power unattainable. There is, however, an interesting amplifier geometry that is simultaneously capable of high average power per unit beam area, high peak power per unit beam area, and large beam diameters. This geometry is shown in Fig. 31. In this case, a single disk of a conventional disk amplifier is divided into two or more parallel plates. A gas coolant, typically helium or nitrogen, is flowed through the channels made by the parallel plates so that the glass heat is removed by conduction through the large flat surfaces of the plates, producing a thermal gradient normal to the surface of the plate. If the plates are infinite in lateral extent, the thermal gradient produces no optical distortion, since all rays of the beam will sample equally the stress field of the plate. In practice, finite plates will show little distortion except within one or two plate-thicknesses of an edge.

To calculate the average-power capability of such an amplifier, we must first determine the thermal deposition per unit-volume of glass for the operating condition desired. Figure 32 shows the origin of the thermal deposition for the flashlamp operating point of Figs. 1 and 2. Thus, for each joule of potentially available energy at $1.06\text{ }\mu\text{m}$, there is two-thirds of a joule of thermally deposited energy in the glass. If we assume that the peak stored energy fraction is 0.5, then, for each joule of available inversion in the ${}^4\text{F}_{3/2}$ state, there are 1.37 J of thermal deposition in the glass. The material parameters needed to calculate the temperature and the thermally induced stresses are presented in Table 4. Since glass possesses a rather high product of density and specific heat, the deposition of a joule of thermal energy per cubic centimeter will raise the temperature by only a fraction of a degree. Thus, high-repetition-rate operation can be considered as steady-state operation once the operating temperature is reached.

Fig. 31. Brewster-angle disk amplifier geometry suitable for attaining high-peak-power pulses and high-average-power output, simultaneously.

Fig. 32. Energy distributions in Nd:glass pumped with a xenon flashlamp, showing energy fractions of lattice heating and stored energy.

Table 4. Properties of selected glasses and crystals (300 K).

	Density, ρ (g/cm ³)	Specific heat (J/g-°C)	Thermal conductivity (W/m-°C)		Thermal expansion α (10 ⁻⁶ /°C)	$\Delta n/\Delta T$ (10 ⁻⁶ /°C)	$\Delta \epsilon/\Delta T$ (10 ⁻⁶ /°C)	Young's modulus, E (kg/mm ²)	Strength, S_T (kg/mm ²)	Poisson's ratio, ν	Index of refraction n	Thermal shock, ^a R_T (W/m)	
			300 K	100 K								300 K	100 K
Glasses													
ED-2	2.54	0.92	1.35	—	8.0	+2.9	8.0	9 190	~10	0.24	1.56	140	—
LG-750	2.82	0.72	0.62	—	11.4	-5.1	0.8	5 150	(5.5)	0.26	1.53	43	—
Q-100	3.20	0.80	0.82	—	9.6	-4.6	±0.5	7 150	(6.5)	0.24	1.56	59	—
Fused quartz	2.20	0.75	1.38	—	0.55	+9.6	9.9	7 190	5.0	0.17	1.45	1 450	—
Zerodur	2.53	0.82	1.64	—	0.12	+14	14.1	9 060	9.3	0.24	1.54	10 600	—
Crystals													
Al ₂ O ₃	3.99	0.75	42	400	~5.0 ^b	~+1.2 ^b	~5.0 ^b	35 230	~55	0.254	1.76	10 000	100 000
MgO	3.59	1.0	59	267	11.0	+2.6	33	25 456	~37	0.36	1.67	5 000	22 600
YAG	4.55	0.6	13	58	7.8	+7.3	13.6	31 725	~20	0.25	1.81	790	3 550
BeAl ₂ O ₄	3.69	—	23	—	~6.5 ^b	—	—	44 550	~60	(0.25)	1.73	~3 570	—
MgF ₂	3.18	1.0	21	100	~10 ^b	~+2.0 ^b	~6.9 ^b	17 625	5.4	0.27	1.36	~470	~2 240
LiYF ₄	3.99	0.79	6	20	~10 ^b	~3.0 ^b	~2.9 ^b	7 650	3.4	0.33	1.45	~180	~600

^a $R_T = S_T(1 - \nu k/E\alpha)$.

^b Average over crystal axes.

^c Axis value.

If the two large, flat surfaces of the plate are held at constant temperature by the coolant flow, and if the energy-deposition profile through the thickness of the plate is uniform, then the temperature profile in the slab is just

$$T = T_0(1 - 4z^2/t^2) \quad (8)$$

where t is the thickness of the plate and z is distance measured normal to the plate with $z = 0$ at the midplane. T_0 is given by

$$T_0 = \frac{P_v t^2}{8\kappa} \quad (9)$$

Fig. 33. Specific thermal power deposition in a glass or MgF_2 crystal slab as a function of slab thickness for different values of temperature rise, T_o .

where P_v is the thermal power deposited per unit volume, and κ is the thermal conductivity. Figure 33 plots this relationship, showing the allowable thermal deposition as a function of t for various values of the temperature rise, T_o . The temperature rise affects both the bulk of the glass and the Nd ion. The plate is compressively loaded at the center, while the surface of the plate is in tensile stress. Since glass is strong in compression but comparatively weak in tension, it is the tensile stress at the surface that concerns us. It is easy to show⁷⁵ that the peak tensile stress occurs at the surface and is

$$\sigma_t = \frac{2\alpha T_o E}{3(1 - \nu)} \quad , \quad (10)$$

where α is the coefficient of thermal expansion, E is the modulus of elasticity, and ν is Poisson's ratio. This relationship is plotted as a function of T_o in Fig. 34. For a T_o of 90°C , the tensile stress is approximately $4.45 \times 10^7 \text{ N/m}^2$. This stress is approximately 25% of the yield stress of unstrengthened glass. Many glass compositions can have surface compressive layers applied. For example,⁷⁶ an ion-exchange process applied to ED-2 produces a surface compression of approximately $3 \times 10^8 \text{ N/m}^2$ with no loss of optical quality of the finished plate. Thus, operation with values of T_o in the range of 60 to 180°C is possible.

Heating the glass induces the thermal population into the $^4I_{11/2}$ terminal state of the $1.06\text{-}\mu\text{m}$ transition. This both reduces the gain coefficient of the material and reduces the availability of the energy stored in the $^4F_{3/2}$ state. The magnitude of this effect is shown in Fig. 35.

Fig. 34. Peak tensile stress of the surface of a uniformly-heated, face-cooled glass slab, as a function of the temperature rise, T_0 .

Figure 35 (a) shows the fraction of Nd ions residing in the $^4I_{11/2}$ level as a function of temperature over the range 250 to 500 K. Figures 35(b) and 35(c) show the relative gain coefficients as a function of temperature, assuming excited $^4F_{3/2}$ J-level densities of 5.27×10^{17} ion/cm³ (100 mJ/cm³) and 1.05×10^{18} ion/cm³ (200 mJ/cm³), respectively. The curves in Figs. 35(b) and 35(c) are calculated for glass Nd ion densities of 2, 5 and 10×10^{20} ion/cm³. From these figures we conclude that for cases of high excitation density (200 mJ/cm³) and low glass doping, operation at much over 450 K will result in a substantial performance degradation. Performance degradation can occur at even lower temperatures for cases of lower excitation density and/or high glass dopings. Thus, in view of the large temperature drop in the boundary layer of the coolant flow, operation with T_0 much above 90° C will require the inlet gas temperature to be reduced below the ambient of 300 K.

To place the discussion in context, we have considered four particular examples with widely varying characteristics in Table 5. From this table, it is clear that Nd:glass can, under the proper conditions, generate very high average power. Without resorting to particularly complex mechanical supporting structures, the 0.5-cm-thick plates are probably limited to amplifiers of 10-cm diameter, while 4-cm-thick plates can be used in apertures up to 80 cm.

Slab thickness (cm)	Thermal deposition (W/cm ²)	Repetition rate (Hz)	Peak stored energy density (mJ/cm ³)	Glass thermal stress (N/cm ²)
0.5	12	100	90	4.45×10^7
1.0	3.16	10	237	4.45×10^7
2.0	0.76	3	190	4.45×10^7
4.0	0.195	1	146	4.45×10^7
$T_0 = 90^\circ\text{C}$				
Peak stored energy fraction = 0.5				

Table 5. Four examples of the performance of repetitively-pulsed, disk-type amplifiers.

Fig. 35. (a) Population density in $^4I_{11/2}$ level as a function of temperature; (b) and (c) relative gain coefficient as a function of temperature; (b) assumes an excited state $^4F_{3/2}$ population density of 5.27×10^{17} ion/cm³; (c) assumes an excited state $^4F_{3/2}$ population density of 1.05×10^{18} ion/cm³.

A Nd:glass laser operating at high average power may also require harmonic generators. Thus, it is useful to examine how one might construct a harmonic generator to operate at high average power. The principle here is the same as the cooled laser-glass plates; however, some extra consideration of the details is in order. When a nonlinear optical crystal heats, the optimum phase-matching angle changes, thus producing a deviation from optimum phase matching and a loss of harmonic-conversion efficiency. The full-width half-maximum-levels of the temperature tuning curves are typically in the range from a few to tens of degrees centigrade. Thus, the temperature must be held constant to about one-tenth of this value, or 1 to 5°C.

Figure 36 shows a simple method for accomplishing the heat removal and temperature control. The allowable temperature rise is calculated as for the glass plates, with $P_v = I_{ave}\gamma$, where I_{ave} is the average optical power through the nonlinear crystal, and γ is the optical loss coefficient. Figure 37 shows I_{ave} plotted as a function of crystal thickness, t , for various materials. Clearly, very high average power is available through the use of these techniques. When the nonlinear optical crystal is separated into several parallel plates, attention must be given to maintaining very close parallelism, and the phase-matching angle of the individual plates must be coincident with the surface normal to within 30 to 50 μ rad, if KDP-type materials are used. Ninety-degree phase-matchable materials relax these requirements significantly. In addition to precision fabrication and assembly, consideration must be given to assuring proper phase relationship between the 1ω and 2ω waves reaching each successive crystal plate, since the coolant gas possesses some optical dispersion. The phase shift, $\Delta\psi$, in the coolant gas is

$$\Delta\psi = \frac{2\pi}{\lambda_2} (n_{2\omega} - n_\omega) s, \quad (11)$$

where $n_{2\omega}$ and n_ω are the indices of refraction of the coolant gas, and s is the total path length of gas between crystals. If we assume that $\Delta\psi \leq \pi/10$ will result in no harmonic generation degradation, then

$$s \leq \frac{\lambda_1}{40\Delta n}. \quad (12)$$

Fig. 36. Conceptual design of a high-average-power harmonic generator using transverse-flow cooling.

The value of s thus defined is shown for a variety of coolant gases in Table 6. Clearly, air is a rather marginal coolant if more than two coolant channels are required. However, helium as a coolant at 1 atm places almost no restriction on the design of the harmonic-generation module.

Table 6. Coolant gases for high average power harmonic conversion.

Coolant gas at 1 atm (273 K)	Total path length, $s(\text{cm})$, for $\Delta\psi = \pi/10$
Air	0.68
Argon	0.59
Neon	6.20
Helium	11.60

Fig. 37. Calculated specific average power (W/cm^2) throughput of a flow-cooled harmonic generator as a function of crystal thickness, for KDP, KD*P, and CD*A nonlinear crystal materials.

4 System Architectures

Most large Nd:glass fusion laser systems constructed to date have utilized the master-oscillator power-amplifier chain (MOPA) as the basic building block. An example is the component layout of the 15-kJ Nova laser MOPA chain, which is shown schematically in Fig. 38. A MOPA chain consists of a master oscillator, which generates a well-controlled low-energy pulse for amplification, and a series of power amplifiers to increase the beam energy. The clear apertures of the power amplifiers increase stepwise down the chain to avoid optical damage as the beam energy grows. To minimize the effects of small-scale self-focusing and to maximize the output fluence, optical-relay spatial filters are placed between the amplifiers along the chain. Laser oscillation in the chain is prevented by the appropriate placement along the chain of Faraday rotators and polarizer plates. To construct laser systems that provide more energy than can be obtained from a single MOPA chain, or to provide for multibeam irradiation geometries, the output from a small MOPA chain is split into the desired number of beams; each of these beams is then used to drive a full MOPA chain.⁷⁷ An alternative system concept that uses components of MOPA chains consists of dividing the initial beam into two beams, followed by amplification, splitting, amplification, etc., until the desired number of beams and total energy are obtained. The technical and cost effectiveness of the various system configurations have been studied and discussed elsewhere.^{78,79}

Fig. 38. Schematic layout of the 15-kJ Nova MOPA chain (master oscillator not shown). Curves below layout show beam energy as a function of component position along the chain, the normalized cost, and the energy per unit cost in J/\$1000.

Figure 38 gives the impression, and correctly so, that a MOPA chain is very complex. The total number of components is quite large, and the chain contains a large number of optical surfaces (here, over 200). It is an inherent property of the MOPA chain that each component along the chain interacts only once with the optical pulse as it passes through. The curves in Fig. 38 show the integral of cost (normalized to unity) and the incremental cost effectiveness (joules per thousand U.S. dollars) along the chain. These curves tell us that the large-output power amplifiers with 46-cm apertures contribute one-half of the output energy, but consume only one-third of the chain cost. The larger the aperture, the greater the cost effectiveness: the cost is (approximately) a linear function of the diameter, while the output energy scales (roughly) as the *square* of the aperture. These curves also tell us that a substantial cost is involved in transporting the beam from the last amplifier to the target. To design and construct more cost-effective Nd:glass laser systems, it is clear that we must pursue system architectures that contain very few components and optical surfaces, and that use cost-effective large-aperture power amplifiers to provide both small and large signal gains.

Figure 39 shows artist's sketches of four different types of "multipass" laser system architectures that meet these criteria. Figure 39(a) shows a three-pass Cassegrainian design, in which the magnification of the telescope and the amplifier gain are adjusted to provide for efficient energy extraction in three passes. This axisymmetric concept is exceptionally compact, but requires very careful treatment of parasitic oscillations. It appears that the Nd:glass gain medium is appropriate for use in this type of system design. Figure 39(b) shows the axisymmetric, switched regenerative multipass amplifier in which a small injected signal is passed repetitively between the end mirrors, and through the large disk amplifier, spatial filter, active switch, and polarizer plate. When the seed pulse is adequately amplified, the switch is activated, and the pulse is deflected out of the cavity. While conceptually attractive, this design requires the development of a low-loss, large-aperture switch; switch designs based on an array of large-aperture Pockels cells and on other technologies are under study at our Laboratory. Figure 39(c) shows an architecture proposed by M. Summers,⁸⁰ which we have named the "reflex ring." It consists of a large-aperture power-amplifier module, a dual-purpose spatial filter and beam-expanding telescope, and a set of only four mirrors. In operation, a small-diameter input pulse is inserted into the ring through a small hole in the input mirror, M1. The pulse is amplified, is "cleaned up" and magnified in diameter in the filter/telescope, and is then reflected around the ring of mirrors back to the input mirror, M1. As it reflects from this mirror, the beam acquires a small hole in its center and passes through the ring again. The beam magnification and amplifier gain have been chosen in such a way that, at the telescope output, the diameter of the hole in the center of the beam exceeds the outer diameter of mirror M2. The beam therefore propagates past this mirror without reflecting and escapes from the ring. The major advantage of this concept is that there is no requirement for a large-aperture switch. However, the proper design of the reflex-ring architecture requires careful treatment and management of beam-diffraction effects.

Finally, Fig. 39(d) shows the axisymmetric, regenerative multipass architecture, in which the switching function is accomplished by harmonic conversion.⁸¹ This geometry consists of two cavity mirrors, one of which is a dichroic mirror providing high reflectivity at a wavelength of $1.06\text{ }\mu\text{m}$ and high transmission at the harmonic wavelength of $0.53\text{ }\mu\text{m}$. An amplifier and a spatial filter are positioned within the dichroic resonator, together with an appropriately oriented array of second-harmonic-generation (SHG) crystals. An injected seed pulse at $1.06\text{ }\mu\text{m}$ is amplified upon successive passes through the cavity elements. On the last pass in the direction of the SHG array, the pulse has sufficient intensity to be transformed to $0.53\text{-}\mu\text{m}$ light and exits the laser system. Angle-sequencing and time-multiplexing variations of the harmonically switched regenerative multipass have also been proposed and analyzed.⁸² An attractive feature of this particular regenerative concept is that the switch need not be activated externally to achieve its function. The concept also accomplishes the up-conversion to shorter wavelength which is thought to be necessary for good coupling to fusion targets.

It is important to note that multiple passes through the same laser medium allow the extraction of stored energy to occur at a lower fluence level than that obtainable in a single pass.

Fig. 39. Artist's sketches of four "multipass" laser system architectures: (a) three-pass Cassegrainian design; (b) axisymmetric switch regenerative oscillator design; (c) two-pass "reflex ring"; and (d) axisymmetric regenerative oscillator switched with an array of harmonic-generator crystals.

Since lasers are often limited by damage of output optics, multipassing can result in higher efficiency and lower system cost. The reduction in fluence due to multipassing is illustrated in Figs. 40(a) and 40(b). These figures show the ratio of output fluence to saturation fluence and the extraction efficiency for simple Frantz-Nodvik saturating amplifiers with a fixed loss lumped after the amplifying medium. At each point in the figures, the input fluence has been adjusted to the value that maximizes the extraction efficiency. The figures show contours of the resulting optimum extraction output-fluence ratio and of the optimized extraction efficiency. The whole calculation is done for one pass, Fig. 40(a) and for four passes, Fig. 40(b). The four-pass case has exactly the same extraction efficiency at each point as the one-pass case, but it

Fig. 40. Efficiency and output fluence performance of multipass Frantz-Nodvik amplifiers of specified single-pass, small-signal-gain and lumped-transmission. Curves of constant efficiency and constant output fluence (normalized to the saturation fluence) are given, for (a) single-pass amplifier, and (b) four-pass amplifier.

achieves this extraction at about one-half the fluence level. This can be a considerable advantage in the realization of large laser systems.

The system architectures described here by no means exhaust the possibilities for compact, simple multipass laser systems. However, these few concepts do convey the design philosophy that emerges naturally from consideration of the limitations of MOPA chains. In the service of logical rigor, however, we need to remind ourselves that the ultimate cost effectiveness in laser-fusion systems may lie in the extreme opposite direction from that discussed here. That is, the economies of mass production may ultimately favor a laser-system design made up of the integration of a very large number of very small "laserlets." Suppose that each of these laserlets were capable of contributing, say, a millijoule of energy to the output. Then, a multimegajoule laser system, whose allowed cost is several hundred million dollars, would require the use of several billion laserlets, each costing less than a few cents. As of this writing, no clear outline of such a system concept has emerged, although the proposed use of mass-produced monolithic semiconductor-diode arrays as pump sources, discussed later, is a step in this direction.

5 Improved Solid State Lasers

We conclude this paper by addressing the question: "What must be the technical properties of superior solid state lasers, and how should we go about finding them?" Our remarks are continued in the context of lasers suitable for fusion applications but we believe that many of these considerations apply to other applications as well.

Let us first look at the problem in perspective. The design of an efficient energy storage laser involves the optimal integration of three basic elements:

- the optical pump source, with its particular geometry, spectral irradiance, and duration;
- the activator/sensitizer ions, with their distinctive charge states and free-ion electronic configurations;
- the host medium, with its macroscopic mechanical, thermal and optical properties, and its unique microscopic lattice properties.

These three elements are represented by three circles in Fig. 41. The circles are shown overlapping to emphasize that these elements interact and must be selected self-consistently to achieve a given system performance. We now consider each of these elements in turn.

Fig. 41. Schematic representation of the interactive nature of the three principal elements making up a laser—the pump source, the host material, and the activator/sensitizer ions.

Pump Sources

Very general technical and economic considerations (energy-storage density of 250 to 500 mJ/cm³, material cost allowance of a few dollars/cm³, etc.) lead us to conclude that pump sources of interest to us must be capable of producing several joules of energy per square centimeter of radiating surface. They must do so efficiently and in a time shorter than the fluorescence decay time of the active laser ion. The number of suitably efficient and intense radiation sources is sufficiently limited that these sources tend to dictate the laser energy-level schemes of interest and the types of activators, sensitizers, and hosts that can be used. We have seen already that large-bore xenon flashlamps are inexpensive, efficient broadband light sources capable of producing up to a hundred joules of radiant energy per centimeter of length, with color temperatures of 9000 to 10 000 K, and with characteristic pulse durations of 500 μ s. As noted earlier, computer models exist that accurately simulate the output radiation of xenon flashlamps over a wide range of operating parameters. Such models will be very helpful in assessing new laser systems. A second type of broadband pump source worthy of consideration is the surface discharge in a rare-gas at high pressure,^{83,84} a discharge capable of efficiently generating several tens of joules per square centimeter, with color temperatures of up to 60 000 K and with a characteristic pulse duration of a few microseconds.⁸⁵

In addition to these broadband pump sources, we believe that it is also appropriate to seriously consider injection semiconductor-diode lasers and electron-beam-pumped semiconductor lasers as pump sources. Early theoretical analysis⁸⁶ and experiments⁸⁷ with e-beam-pumped semiconductor lasers showed that an e-beam to laser energy conversion efficiency as high as 26.5% could be achieved at a wavelength of 490 nm using CdS as the semiconductor medium. Golubev et al.⁸⁸ demonstrated a 30% energy conversion at a wavelength of 795 nm in CdTe. Basov and co-workers^{89,90} have reported a beam-conversion efficiency of 25% for a GaAs laser operating at a wavelength of 822 nm. Basov⁹¹ has also reported beam-conversion efficiencies of 10 to 15% for CdS lasers for use in projection TV systems.

As a result of a very large amount of research and development undertaken worldwide, the efficiency and output power of GaAs injection-laser-diodes have increased impressively in recent years. One of the most important innovations introduced has been the large-optical-cavity (AlGa)As-GaAs heterojunction laser diode, described by Kressel et al.⁹² These authors demonstrated power-conversion efficiencies as high as 25% at room temperature with a single-facet output power in excess of a watt at a wavelength of 913 nm. For the pumping of energy-storage laser media, a second important development has been the fabrication of a large number of stripe diodes on a single bar of semiconducting material.^{93,94} This significant increase in the packing density of laser diodes in an array may ultimately lead to pump sources capable of producing perhaps a joule per square centimeter per millisecond of near-infrared (850-nm) radiation, approaching that flux required for efficiently pumping large scale gain media. Pump-source efficiencies of 25% at room temperature and perhaps as high as 50% at -50°C , may be feasible.

It is envisioned that two-dimensional semiconductor-array pump sources could be incorporated into a solid state power amplifier, as shown schematically in Fig. 42. Because they are sources radiating into the half-plane, they possess several advantageous features in comparison with conventional broadband flashlamps. First, the pump radiation is emitted directly toward the gain medium and does not have to be bounced off an intervening reflecting surface. (Even if it proves necessary to use cavity reflectors to direct radiation to the gain medium, these reflectors may be designed with a very high reflectivity at precisely the pump wavelength.) Second, efficient, uniform pumping can be achieved, since absorption can be made to occur only near the center of a single pump transition; pumping in the wings of transitions can be avoided, with a concomitant reduction of the activator-ion density and any ion-ion quenching. Third, these sources offer the possibility of resonantly pumping activators, resulting in very low levels of thermal lattice heating and correspondingly higher pulse-repetition rates. Because these sources tend to operate at a damage-limited peak power per unit area, it is very advantageous (and probably economically necessary) to use these sources only to pump laser ions with exceptionally high metastability (i.e., many milliseconds).

Fig. 42. Artist's sketch of a disk-type high-average-power solid state amplifier, pumped with two arrays of semiconductor laser diodes.

Energy-Level Schemes

Optimum utilization of the various pump sources requires different laser-energy-level schemes. The simplest energy-level scheme for use with the broadband pump sources is shown in Fig. 43, drawn explicitly⁹⁵ for the divalent vanadium ion (V^{2+}) in crystalline magnesium fluoride (MgF_2). Similar spectroscopic features are exhibited by the trivalent chromium ion (Cr^{3+}) in octahedral lattice sites with low ligand field strengths.⁹⁶ This "phonon-terminated" energy level scheme^{97,98} provides broad absorption bands extending continuously upward in energy above the metastable upper laser level (here, the 4T_2) and provides a thermally empty lower laser level (here, excited phonon levels of the 4A_2 electronic ground state). However, the broad spectral linewidth of the laser gain transition in this level scheme is a limitation that deserves further discussion.

The stimulated-emission cross section, σ , of a transition with radiative lifetime, τ_r , and wavelength, λ_L , are related to one another by the expression

$$\tau_r = \frac{\lambda_L^2}{8\pi cn^2 \Delta\nu \sigma} \quad (13)$$

where $\Delta\nu$ is the spectral width of the transition, and n is the index of refraction of the host medium. Recognizing that a large value of τ_r is desirable to maintain high storage efficiency while

Fig. 43. Single-coordinate energy-level diagram of the V^{2+} ion placed in a lattice site of octahedral O_h symmetry. Absorption and emission spectra for $V:MgF_2$.

pumping, we ask, "How large can τ_r be, consistent with other technical requirements?" In approximate terms, we require $\sigma \geq 0.5 \times 10^{-20} \text{ cm}^2$, corresponding to a saturation fluence $\phi_s \leq 40 \text{ J/cm}^2$ at a wavelength of $1 \mu\text{m}$. This fluence limit is required to achieve efficient and practical energy extraction in the presence of nominal damage fluences of 80 J/cm^2 at 15 ns . Thus,

$$\tau_r \leq 1.2/\Delta\nu, \quad (14)$$

where τ_r is in seconds and $\Delta\nu$ is in wavenumbers. The broad linewidths of phonon-terminated transitions (typically 1000 cm^{-1}) limit energy storage times to about a millisecond for reasonable stimulated emission cross section values. However, transition linewidths of 10 to 20 cm^{-1} are possible for rare-earth ions in crystalline matrices, and energy-storage times as long as tens of milliseconds may be obtained along with acceptable stimulated-emission cross sections.

These considerations prompt us to consider the alternative laser-energy-level schemes shown in Fig. 44. Figure 44(a) shows a classic four-level laser scheme, in which the activator ion provides both broad absorption pump bands and a narrowband laser transition terminating on a thermally empty lower laser level. (Examples of such activator ions are the divalent⁹⁹ rare-earth ions Dy^{2+} , Tm^{2+} , and Sm^{2+} .) The major limitation of these schemes is excited-state absorption¹⁰⁰ at pump and laser transition wavelengths. These deleterious processes are avoided

Fig. 44. Energy level schemes for solid state lasers: (a) four-level laser with single activator ion; (b) four-level laser with sensitizer/activator ion pair; (c) four-level laser at ambient temperatures with activator ion pumped with narrowband source; and (d) four-level laser at low temperature with activator ion pumped with narrowband source.

in the scheme shown in Fig. 44(b). Here, a sensitizer ion provides efficient broadband absorption of pump radiation and transfers excitation energy to the activator ion. The latter is free of energy levels that could lead to excited-state absorption at either pump or laser wavelengths. (An example of this scheme is the $\text{Yb}^{3+}/\text{Cr}^{3+}$ activator/sensitizer pair.¹⁰¹) Due to the high source color temperature and short discharge duration available when using surface discharge sources, activator ions may be used that have upper laser level lifetimes of only tens of microseconds and visible and near-UV wavelength laser transitions.

The energy-level schemes shown in Figs. 44(c) and 44(d) are appropriate for use with the narrowband semiconductor laser pump sources. The first of these is a classic four-level laser scheme, in which the pump excites a level lying just above the upper laser level. The narrowband laser transition terminates on a level thermally unoccupied at ambient temperature. (An example of the scheme is a Nd^{3+} activator ion pumped with GaAs semiconductor diode lasers.¹⁰²) The second of these schemes shown in Fig. 44(d) shows pumping between the ground crystal field split (Stark) level and an excited Stark level of a higher-lying electronic state. Stimulated emission takes place between the lowest metastable Stark level and an excited Stark level of the ground state. Here, the amount of pump energy transformed into lattice heat is an absolute minimum. This scheme, therefore, provides an exceptionally high utilization of pump energy and relatively high pulse-repetition rates. (An example of this scheme is an Yb^{3+} activator¹⁰³ pumped with GaAs semiconductor diode lasers.)

Many variations of these schemes can be envisioned; indeed, even schemes utilizing nonlinear extraction techniques can be proposed. However, those described above provide a useful framework in which to identify interesting types of activators and sensitizers.

Activator/Sensitizer Ions

From the luminescence literature, we can make a preliminary list of the types of activator and sensitizer ions of interest. These are summarized in Table 7. The iron group (3d) transition metal ions are characterized by ground electronic configurations formed by equivalent d electrons. The particular ions with configurations containing 1, 3, 5, 7, and 8 electrons are well-known to luminesce when placed in various transparent solids. These ions are characterized by one or more broad absorption bands lying in the visible and near-infrared spectral regions and often exhibit metastable electronic levels capable of emitting broadband fluorescence in the red and near-infrared spectral regions.¹⁰⁴ These ions may serve as either activator or sensitizer ions for use with broadband pump sources. Although the literature is considerably more silent concerning the luminescence properties of the analogous 4d and 5d metal ions, several of the more promising of these ions are listed in Table 7. Guidance in the selection of candidate activator or sensitizer ions can be greatly enhanced through the use of the energy-level diagrams for equivalent d^n electron configuration as a function of ligand-field strength, discussed in detail by Tanabe and Sugano.¹⁰⁵

Another group of ions well-known for their luminescence is the post-transition groups with closed-shell ground configurations and metastable p -like first excited electronic levels. This group is typified by the monovalent Tl, In, and Ga ions and the divalent Sn and Pb ions. These ions are characterized by spin-forbidden vibronic absorption transitions lying in the near-UV and emit in fluorescence bands in the short-wavelength visible region.¹⁰⁶ Fluorescence lifetimes depend strongly on the ligand and on temperature, but generally span the range from a few to many tens of microseconds. A third group of interesting ions consists of the d^{10} closed-shell ions, typified by Cu^{1+} and Ag^{1+} , which possess d^9 's first excited electronic levels. An electric dipole transition between ground and the first excited level is parity-forbidden in these ions, so that weak phonon-terminated fluorescence transitions in the UV/blue spectral region are often observed in doped crystals.¹⁰⁷

To design lasers exploiting narrowband semiconductor pump sources, most of the trivalent and selected divalent rare-earth ions appear to be the best activator ions. We have already cited

Table 7. Types of activator/sensitizer ions.

Metals	Ground configuration	Transition type	3d ions	4d ions	5d ions
Transition	d ¹	d-d	Ti ³⁺	—	—
	d ²	d-d	V ³⁺	—	—
	d ³	d-d	V ²⁺ , Cr ³⁺ , Mn ⁴⁺	Mo ³⁺	Re ⁴⁺
	d ⁴	d-d	—	Ru ⁴⁺	Os ⁴⁺
	d ⁵	d-d	Mn ²⁺	—	Ir ⁴⁺
	d ⁶	d-d	Co ³⁺	Rh ³⁺	—
	d ⁷	d-d	Co ²⁺	—	—
	d ⁸	d-d	Ni ²⁺	Pd ²⁺	Pt ²⁺
Post transition	IB d ⁹	d-d	Cu ²⁺	—	—
	IB d ¹⁰	d-s	Cu ¹⁺	Ag ¹⁺	Au ¹⁺
	IIIA, IVA d ¹⁰ s ²	d-p	Ga ¹⁺	In ¹⁺ , Sn ²⁺	Tl ¹⁺ , Pb ²⁺ , Bi ³⁺
Lanthanide ions (4f ⁿ)	Ground configuration	Transition type	Trivalent	Divalent	
	f ³	f-f	Nd ³⁺	—	
	f ⁵	f-f	Sm ³⁺	—	
	f ⁶	f-f	Eu ³⁺	Sm ²⁺	
	f ⁷	f-f	—	Eu ²⁺	
	f ⁸	f-f	Tb ³⁺	—	
	f ⁹	f-f	Dy ³⁺	—	
	f ¹⁰	f-f	Ho ³⁺	Dy ²⁺	
	f ¹¹	f-f	Er ³⁺	—	
	f ¹²	f-f	Tm ³⁺	—	
	f ¹³	f-f	Yb ³⁺	Tm ²⁺	

the use of Nd³⁺ and Yb³⁺ ions as activator ions for use in the laser schemes illustrated in Figs. 44(c) and (d), respectively. Trivalent rare earth ions, such as Eu³⁺, Tb³⁺, Dy³⁺, and Sm³⁺ have long-lived metastable levels in the visible spectral region and are likely ions for use with short-wavelength semiconductor pump sources, such as CdS.

Host Media – Thermal, Mechanical, and Linear Optical Properties

One of the most limiting features of the Nd:glass laser medium is its relatively low average-power capability. This limitation comes from the characteristically low thermal conductivities of glasses (i.e., 1 W/m – K). Considering the laser amplifier geometry of Fig. 31, we can combine Eqs. (9) and (10) and write the ratio of the thermally induced tensile stress, σ_t , to the tensile yield strength S_T of the material as

$$\frac{\sigma_t}{S_T} = \left[\frac{S_T k (1 - \nu)}{\alpha E} \right]^{-1} \frac{P_v t^2}{12} = [R_T]^{-1} \frac{P_v t^2}{12} \quad (15)$$

The parameter R_T is defined as the thermal shock resistance parameter, which we adopt here as a useful figure of merit for a material. For a specific uniform thermal loading, P_v , of a slab of

thickness, t , a large value of R_T (W/m) will lead to a more favorable σ_r/S_T ratio. Since, for properly prepared materials the ratio S_T/E does not vary widely, there are two main strategies for achieving a large R_T and thus a high-average-power handling capability. First, materials could be chosen which have coefficients of thermal expansion a factor of 10 to 100 below conventional laser glasses. Second, crystalline materials can be chosen which exhibit thermal conductivities 10 to 100 times larger than conventional laser glasses. Table 4 on page 26 illustrates both types of materials.

It should be noted here, however, that these two strategies are not equivalent. The low coefficient of thermal expansion lowers the surface tensile stress of the slab without lowering the centerline temperature. Thus increasing the average power per unit volume increases the centerline temperature of the slab. In contrast, a high thermal conductivity lowers the tensile stress by lowering the temperature gradient and thus the centerline temperature.

Thus far Nd:glass development has been directed toward developing materials with large stimulated-emission cross sections, low nonlinear refractive indices, or "athermal" optical characteristics where the change in optical path length with temperature is minimized. ("Athermal" in this context means that $ds/dT = 0$, where s is the optical path length and T is the operating temperature range. This characteristic is very important if Nd:YAG is to be replaced with Nd:glass in small cylindrical rod lasers, but it is almost irrelevant for high-average-power amplifiers using the geometries of Figs. 7, 8, and 9.) Little effort to date has been expended on minimizing the coefficient of thermal expansion, yet there are well known glass compositions with low coefficients. Table 4 shows some of the extremely low coefficients of thermal expansion materials such as fused silica and glass ceramics¹⁰⁸ of which Zerodur¹⁰⁹ is an example. If glass ceramics are to be used as laser materials, significant compositional development would be required to control light scattering and to optimize the laser properties of the active ion.¹¹⁰ However, it is probable that unless the active ion can be induced to deposit preferentially in the crystalline phase, the choice of laser active ions would be limited to those that perform well in glassy or poorly ordered media—namely, neodymium and ytterbium. In both glasses⁷⁶ and glass ceramics¹¹¹ it has proven feasible to strengthen them by forming surface layers that are in compression by ion exchange techniques. Thus the potential exists for very high average power operation.

Achieving high average power through high thermal conductivity requires the choice of ordered or crystalline media. As shown in Table 4, representative oxide and fluoride crystals exhibit thermal conductivities which are typically 10 to 100 times that found in typical laser glasses, and thus have a potential for operating at a correspondingly higher average power. Also attractive is the fact that, in general, the thermal conductivity of crystalline materials increases as the operating temperature of the materials is lowered, which further enhances the average power handling capability. However, to achieve high overall laser system efficiency, careful consideration must be given to the ratio of thermal deposition to extractable stored energy in the medium as well as to the operating temperature. Appendix C contains a detailed discussion of the efficiency impact of low temperature operation. Consideration might also be given to strengthening crystalline materials by modifying surface layer composition through ion exchange or ion implantation. If compression layers could be achieved on crystalline materials as on glasses and glass-ceramics, then the average power capability would be further increased.

The crystal must also possess favorable optical properties. For use in the Brewster-angle disk geometry (see Fig. 31), isotropic (cubic) or uniaxial crystals with low stress-optical-coefficients are most desirable. In certain classes of cubic crystals, it is also possible to choose a crystal orientation that will eliminate stress-induced birefringence for even a non-uniform thermal deposition profile across the plate.¹¹²

Host Media—Nonlinear Optical Properties

In developing new solid state laser materials for high peak power as well as high average power and high efficiency, it is necessary to carefully consider the nonlinear optical properties of potential host candidates. From this point of view, it is necessary to know substantially more than just the nonlinear refractive index of the proposed medium in order to determine which

hosts are acceptable. Since overall laser system efficiency is of prime importance, the amplifier will have to operate at high extraction efficiency and thus operate heavily saturated. Since small signal gains of 25–100 are the maximum that can be practically managed in a laser system with long pump and storage times, the maximum fluence in the system will be in the range of a few to several saturation fluences. Thus in order to determine what are allowable n_2 values, we must also know the saturation fluence of the laser transition, the peak stored energy density, and the pulse duration. The B integral for a single pass saturating amplifier can be written as

$$B = \frac{8 \times 10^8 \pi^2 n_2 S^2}{\lambda n c \tau E_d} B' \quad (16)$$

where n_2 is in esu

S is the saturation fluence in J/cm^2

τ is in seconds

E_d is the peak stored energy density in J/cm^3 , and
length units are in centimeters.

B' is calculated segment by segment in a saturating amplifier and is presented on the graphs of Fig. 45 and 46. In these figures, the left ordinate and solid curves display the extraction efficiency as a function of the normalized input fluence (ϕ_{in}/S) for various values of the small signal gain. The right ordinate and the dashed curves show B' again as a function of input fluence

Fig. 45. Extraction efficiency and relative B integral (nonlinear effects) for a saturating laser amplifier as a function of the fluence into the amplifier. Losses corresponding to an unpumped transmission of 0.9 are uniformly distributed along the amplifier. Extraction efficiency (solid curves) and relative B integral (dashed curves) are shown for values of the small signal gain (pumped/unpumped) ranging from 1.2 to 200. Extraction falls at high fluence because of the losses.

Fig. 46. Extraction efficiency and relative B integral (nonlinear effects) for a saturating laser amplifier as a function of the fluence into the amplifier. Losses corresponding to an unpumped transmission of 0.8 are uniformly distributed along the amplifier. Extraction efficiency (solid curves) and relative B integral (dashed curves) are shown for values of the small signal gain (pumped/unpumped) ranging from 1.2 to 200. Extraction falls at high fluence because of the losses.

for the same values of small signal gain. Figure 45 is for a passive amplifier transmission of 90% and Fig. 46 is for 80%. This spans most reasonable operating conditions. The calculation was carried out for the maximum B' at the end of a rectangular output pulse. It is thus correct for any pulse shape of the same total energy and the same peak power as long as the pulse goes to zero immediately after the peak power point is reached. The calculated values for Gaussian pulses are typically 25% lower than for square pulses.

If we assume a maximum B of 2.5 radians between spatial filters, then Eq. (16) becomes

$$SN_2B' = \frac{Sn_2B'}{n} = \frac{2.5 \lambda c \tau (E_d/S)}{8 \times 10^8 \pi^2} \quad (17)$$

Written in this way, the explicit dependence of n_2 (or $N_2 = n_2/n$) on the achievable peak stored energy density E_d and on the saturation fluence S is abundantly clear. Equation (17) is plotted in Fig. 47.

Equation (17) strictly applies only to a linearly-polarized laser beam within the laser medium where E_d and S are the medium values. For circularly polarized light in an isotropic medium, the effective n_2 is 2/3 of the value for linear polarization.^{113,114} Thus n_2/n should be replaced by 2/3 (n_2/n) for this case. For calculations involving Brewster-angle disk lasers, remember that the fluences used are the fluences in the medium which are 1/n times the fluence of the beam in air outside the disk.

Fig. 47. The product N_2SB' ($= n_2SB'/n$) is a linear function of the ratio E_d/S of stored energy density to saturation fluence, with a coefficient which is proportional to the pulse width. Low nonlinear effects result from high stored energy densities and low saturation fluences.

As an example of the foregoing discussion, let us consider a medium to be used in an amplifier of small signal gain 10, passive transmission 90%, which will operate at 70% extraction efficiency. For these values Fig. 45 gives a value of $B' = 0.45$. Further suppose that we can pump the laser medium to 0.25 J/cm^2 , that S for the laser transition is 10 J/cm^2 , and that we require a pulse duration of 10 ns. From Fig. 47 we find that $n_2/n < 0.52 \times 10^{-13}$. In Table 8 we have listed the linear and nonlinear refractive indices of some representative oxide and fluoride crystals and glasses. For the example above, it is clear that all the fluorides and some of the oxides meet the requirement. It should be noted that the results are, of course, sensitive to the peak stored energy density (linearly) and quite sensitive to the saturation fluence (quadratically). In general, we can conclude that both oxides and fluorides are worthy of development. Both oxides and fluorides are quite applicable for pulse durations 10 to 15 ns or longer as long as S is reasonable, but only fluorides should be developed for operation at $< 10 \text{ ns}$. Fluorides offer lower values of n_2/n and lower growth temperatures but have lower mechanical strength than oxides. Ultimately, the choice will be dictated by the saturation fluence, the achievable stored energy density, and ease of growth.

Crystal Hosts

Based on the preceding discussion of desirable space and point group symmetries, linear and nonlinear optical properties, and thermal and mechanical properties of crystalline host media, we present a listing of potentially useful cubic and uniaxial crystal types in Tables 9 and 10.

Table 9 lists fluorine-based crystals generally characterized by low values of linear and non-linear refractive indices. For these systems, note that several different alkali, alkaline earth, transition metal, and lanthanide ions may be utilized, thus providing a fairly large number of possible host crystals. Among these crystal types, the simple $M^I M^{II} F_3$ cubic perovskites and $M_2^I M^{II} M^{III} F_6$ cubic elpasolites, which possess purely octahedral activator sites (M^{II} and M^{III} , respectively), are particularly attractive for achieving long energy-storage lifetimes. Table 10 lists some oxygen-based crystal types analogous to the fluorine-based crystals of Table 9. As we

Table 8. Index of refraction figures of merit.

	n_d (588 nm)	ν	n_2 (1060 nm) (10^{-13} esu)	n_2/n (10^{-13} esu)
Crystal				
YAG ($Y_3Al_5O_{12}$)	1.835	51	3.2	1.73
Al_2O_3	1.768	72	1.1	0.60
$BeAl_2O_4$	1.740	73	0.8	0.48
MgO	1.74	55	2.8	1.6
$MgAl_2O_4$	1.68	61	2.1	1.2
MgF_2	1.378	104	0.30	0.22
$LiYF_4$	1.457	90	0.60	0.41
LiF	1.392	99	0.35	0.25
NaF	1.326	85	0.43	0.32
CaF_2	1.434	95	0.65	0.45
SrF_2	1.438	92	0.60	0.42
Glass				
ED-2 (S)	1.561	56	1.41	0.90
LG-750 (P)	1.516	68	1.08	0.71
LHG-10 (FP)	1.454	90	0.58	0.40
B128 (FB)	1.335	100	0.31	0.23
S = Silicate, P = Phosphate, FP = Fluorophosphate, FB = Fluoroberyllate				
Crystal Source: M. J. Weber, D. Milam, W. L. Smith, <i>Opt. Eng.</i> 17, 463 (1978).				
Glass Source: S. E. Stokowski, R. A. Saroyan, and M. J. Weber, <i>Nd-doped Laser Glass Spectroscopic and Physical Properties</i> , Lawrence Livermore National Laboratory, Livermore, Calif., Report M-95 Nov. 1981				

have seen from Table 4, oxide crystals are generally characterized by larger values of n_2 , n , and n_2/n than are the fluorides, but often have superior thermo-mechanical properties. The use of many of these crystal types may prove effective only when bearing activator ions characterized by relatively low saturation fluences and/or when used to produce output pulses with durations greater than 10 nsec. At the present time, little data are available on the mechanical, thermal and optical properties of many of the crystals cited in Tables 9 and 10. Clearly this situation will have to be remedied if we are to quantitatively evaluate their utility.

To construct highly energetic lasers, it will of course be necessary that large, doped, high-optical-quality crystals are growable with high yield. It seems to us that the prospect for successful crystal growth scaling would be greatest for crystals that melt congruently; and those with relatively low melting temperatures (e.g., $T_m \leq 1500^\circ C$). Such temperatures permit the use of a wide variety of crucible materials and growth methods. We are greatly encouraged by the progress made in recent years in the growth of high-quality, large diameter (>10 cm) $LiYF_4$ crystals doped with trivalent rare earth ion activators.¹¹⁵ Effort is now also being directed toward the growth of large aperture MgF_2 crystals doped with Co^{2+} ions. Growth of large-aperture oxide crystals has also been achieved in recent years (Nd:GGG up to 15 cm diameter and undoped Al_2O_3 up to 30 cm diameter). While the prospect for large scale growth is positive, development of large-aperture doped crystals will require the investment of considerable resources and will take several years to accomplish. It is therefore extremely important that candidate systems be thoroughly evaluated on the basis of small-scale spectroscopic and laser experiments coupled with extensive modeling, before a specific crystal system is selected for scaled development.

Table 9. Some types of fluorine-based crystals potentially useful as laser hosts.

Type	Symmetry	Example
$M^{II}F_2$	cubic tetragonal	CaF_2 MgF_2
$M^{II}F_3$	hexagonal	LaF_3
$M^IM^{II}F_3$	cubic tetragonal	$KMgF_3$ $NaZnF_3$
$M^IM^{III}F_4$	cubic tetragonal hexagonal	$NaYF_4$ $LiYF_4$ $\beta-KLaF_4$
$M^IM^{II}F_4$	cubic tetragonal	K_2CaF_4 K_2MgF_4
$M^{II}\bar{M}^{II}M_2^{III}F_{10}$	cubic	$BaCaY_2F_{10}$
$M_1^I\bar{M}_1^{II}M_2^{III}F_{12}$	cubic	$Na_3Li_3Al_2F_{12}$
$M^{II}\bar{M}_2^{II}M_2^{III}F_{12}$	cubic	$CaMg_2Al_2F_{12}$
$M_3^I\bar{M}_2^{II}F_{12}$	cubic	$Mg_3Al_2F_{12}$
$M^IM^{II}M^{III}F_6$	cubic	$NaCaYF_6$
$M^I\bar{M}_2^I\bar{M}^{III}F_6$	cubic	K_2NaAlF_6
$M^I = Li, Na, K, Rb, Cs, Tl, Ag$ $M^{II} = Be, Mg, Ca, Sr, Ba, Mn, Zn, Cd$ $M^{III} = Al, Ga, Sc, Y, La$		

Table 10. Some types of oxygen-based crystals potentially useful as laser hosts.

Type	Symmetry	Example
$M^{II}O$	cubic	MgO
$M^IM^{III}O_2$	tetragonal	$NaGdO_2$
$M_2^{III}O_3$	hexagonal	Al_2O_3
$M^{II}M^{IV}O_3$	cubic tetragonal	$SrTiO_3$ $BaTiO_3$
$M^IM^VO_3$	hexagonal	$LiTaO_3$
$M^IM^{III}O_4$	tetragonal	$NaGdO_4$
$M^{II}M_2^{III}O_4$	cubic	$MgAl_2O_4$
$M_2^{II}M^{III}M^VO_6$	cubic	Ba_2GdTaO_6
$M_3^{III}\bar{M}_2^{III}\bar{M}_3^{III}O_{12}$	cubic	$Gd_3Ga_2Sc_3O_{12}$
$M^I = Li, Na, K, Rb, Cs$ $M^{II} = Mg, Ca, Sr, Ba$ $M^{III} = Al, Ga, Sc, Y, Gd, etc.$ $M^{IV} = Ti, Zr$ $M^V = Ta, Nb$		

An Example – V:MgF₂

Prompted by the type of considerations outlined in this paper, we initiated a small effort a few years ago to identify, analyze, and evaluate impurity-doped crystals for use in fusion lasers. Based on the limited absorption and fluorescence data then available in the literature,^{95,97} and on VODEP simulations of amplifier performance, we¹¹⁶ identified flashlamp-pumped vanadium-doped magnesium fluoride (V:MgF₂) as an interesting candidate (see Fig. 43). The fractional energies absorbed by V:MgF₂ for optical depths of 2×10^{20} and 10×10^{20} ion/cm² are shown in Fig. 48 (compare with the Nd:glass absorption data of Fig. 3). We see that the vanadium material is highly absorbing at an optical depth of 10^{21} ion/cm². The VODEP-calculated pumping efficiency of V:MgF₂ as a function of optical depth is shown in Fig. 49 (compare to Fig. 4). Crystal-growth studies¹¹⁷ have shown that solid solutions of up to 9 wt% VF₂ in MgF₂ can be achieved, corresponding to a V²⁺ ion density of 2×10^{21} ion/cm³. Spectroscopic studies¹¹⁸ show that negligible concentration quenching of the V²⁺ radiative fluorescence lifetime of

Fig. 48. Absorption of V:MgF₂ crystal as a function of wavelength, for optical depths of 2×10^{20} and 10×10^{20} ion/cm².

Fig. 49. Fractional energy absorption by V:MgF₂ of xenon flashlamp output energy emitted in two spectral bands, as a function of optical depth.

Table 11. Limiting efficiencies for pumping V:MgF₂ gain medium for two values of optical depth.

Optical depth, V:MgF ₂ (ion/cm ²)	Flashlamp radiative efficiency	Fraction absorbed in V ²⁺	Average quantum efficiency	Maximum pumping efficiency
2×10^{20}	0.75	0.46	0.56	0.19
1×10^{21}	0.75	0.82	0.53	0.33

2.5 ms occurs for ion densities up to 7×10^{20} ion/cm³. Since crystal-slab thicknesses of a few centimeters are of interest, optical depths up to 10^{21} ion/cm² appear to be feasible. Maximum pumping efficiencies for V:MgF₂ (as defined in Table 1) are summarized in Table 11 for the optical depth values of 2×10^{20} and 10×10^{20} ion/cm². A maximum pumping efficiency of 33% can be achieved at an optical depth of 10^{21} ion/cm², compared to 20% for Nd:glass (Table 1). Equally important is the fact that the fluorescence decay of population inversion will be considerably reduced in V:MgF₂, as compared to Nd:glass, because of the long V:MgF₂ fluorescence lifetime. We estimate a peak-stored energy fraction for V:MgF₂ of 0.8, as compared to 0.5 to 0.7 for Nd:glass. Including fluorescence decay, we calculate a limiting energy-storage efficiency of 26% for V:MgF₂, or about 2.3 times more efficient than that of Nd:glass. It was the prospect of attaining such a high energy-storage efficiency that prompted our continued interest in V:MgF₂.

Detailed spectroscopy, laser-amplifier, and tunable-laser-oscillator studies of Moulton¹¹⁸ have shown that the peak fluorescence-emission cross section is $0.4 \pm 0.05 \times 10^{-20}$ cm² (compared to the earlier published⁹⁷ value of 0.8×10^{-20} cm²). The correct cross section corresponds to a saturation fluence of 45 J/cm². While this upward-revised saturation fluence is unwelcome, the exceptionally high optical-damage threshold of this crystal (~ 100 J/cm² for 40-ns pulses¹¹⁹) could probably accommodate the higher saturation fluence. However, Moulton's experiments turned up a much more serious problem with V:MgF₂. Measurement of the small signal gain of a V:MgF₂ amplifier pumped with an argon-ion laser showed that the net cross section (fluorescence minus excited-state-absorption cross sections) was much smaller than the fluorescence cross section. Tuning of a laser oscillator over the measured spectral-fluorescence profile showed a premature termination of the gain on the long-wavelength side of the fluorescence curve. This effect is consistent with the gain measurements and is attributed to an excited-state absorption transition centered beyond the 1.12- μ m fluorescence maximum, with a peak cross section of at least 0.4×10^{-20} cm². (The published value⁹⁷ for the excited-state-absorption cross section is $< 0.3 \times 10^{-20}$ cm².) This large inferred excited-state-absorption cross section will result in a greatly reduced amplifier efficiency as compared with that estimated using spectroscopic data from the literature; it also will result in an unacceptably large thermal heat load in the gain medium. The V:MgF₂ gain medium is therefore unacceptable for our purpose.

Before abandoning V²⁺ as an activator ion, with its very attractive "free-ion" energy-level structure for an energy-storage laser, we need to determine the origin of the excited-state absorption transition and whether or not its wavelength or strength can be manipulated. To get some insight into this problem, it is useful to examine the *d*-electron-level energies of the V²⁺ ion placed in a crystal lattice site with octahedral symmetry and a cubic-crystal field strength, *Dq*.¹⁰⁵ Figure 50 shows the energies of the low-lying levels relevant to our problem. The left-hand ordinate gives energies measured from the ⁴A₂ ground electronic level of the unexcited V²⁺ ion. For fluoride crystals, the value of *Dq* is less than 1200 cm⁻¹ and the ⁴T₂ level lies below the ²E level. The level energies for MgF₂ and two other fluoride crystals are designated by arrows at the appropriate *Dq* values. The shaded widths of the ⁴T₂ and ⁴T₁ levels represent the banded character of the absorption transitions. When the V²⁺ ion is excited to any of its excited states, the electron relaxes rapidly to the metastable ⁴T₂ level. By relaxation of the lattice, this triply degenerate level lowers its energy in the octahedral field, as measured from the ground level. We have illustrated this effect schematically in Fig. 50 by shifting the ⁴A₂ level upward and using the right-hand energy scale. (The ²E and ²T₁ levels should be ignored when considering the excited ion.) The approximate energies of the Stokes-shifted ⁴T₂ $\rightarrow$ ⁴A₂ fluorescence

Fig. 50. Low-lying energies of the electronic levels of V^{2+} as a function of the cubic crystal field strength, Dq . Left-hand ordinate gives energy from 4A_2 ground level of unexcited ion. Right-hand ordinate gives energy differences between levels of the V^{2+} ion excited into the 4T_2 level.

transition (solid line) and the $^4T_2 \rightarrow ^4T_1$ excited state absorption transition (dotted line) of each crystal can now be compared. Consistent with experimental observations, this figure indicates that the $1.12\text{-}\mu\text{m}$ peak (8930 cm^{-1}) of the fluorescence of $V:MgF_2$ lies in the high-energy wing of the $^4T_2 \rightarrow ^4T_1$ excited-state absorption transition. Figure 50 also suggests that an even closer overlap would be encountered in the crystal $V:MnF_2$, due to its lower value of Dq . However, from the present estimates, it appears that excited-state absorption should be less of a problem in the crystal $V:KMgF_3$, due to its larger value of Dq .⁹¹ Experiments are currently underway to test this result; at the same time, we are evaluating alternative vanadium-doped crystals and altogether different ion/host combinations, both within the framework of the simple, but admittedly inaccurate, crystal-field model of Fig. 50 and on the basis of considerably more sophisticated molecular-orbital calculations. As we seek to evaluate other new ion/host combinations, the presence and strength of excited-state absorption transitions can dominate the outcome (as it did in the example of $V:MgF_2$). To permit a comprehensive and efficient search for new solid state laser media, new theories and computational methods must be developed to realistically treat the excited-state dynamics of impurity ions in crystals.

6 Conclusions

From the material presented in this article, we can draw six important conclusions:

- First, it is clear that current Nd:glass amplifiers are far from the fundamental limits of energy-storage efficiency. This is largely because these amplifiers have been assembled, rather than designed, and because optimization—if it was done at all—was intended to maximize amplifier gain coefficient, and not efficiency. Thus, it is clear that much more efficient systems can be designed.
- Second, the cost effectiveness and operability of Nd:glass laser systems seem to improve substantially with size. Indeed 5- to 10-MJ systems comprised of 10 to 20 beams appear to be far more cost-effective than current smaller systems.
- Third, harmonic-generation can be achieved with high efficiency on large systems, greatly enhancing their utility.
- Fourth, Nd:glass systems can be operated at far higher average powers than is generally assumed, if the appropriate amplifier configurations are employed, and if very careful attention is paid to all design details.
- Fifth, improved glass and glass-ceramic compositions can be developed which will allow operation at higher average power than today's laser glasses.
- Sixth, the use of crystalline laser media will relax average-power limitations of Nd:glass by an order of magnitude. In this respect, we are greatly encouraged by the successful growth in recent years of a variety of large crystals; it now seems reasonable to consider the possibilities of large systems using crystalline media.
- Seventh, the feasibility of large single crystals justifies a new systematic search for improved ion/host combinations for new laser media. The continuing improvement in our understanding of the structure and dynamics of luminescent impurity ions in crystals should make possible a systematic search. Thus, a renaissance in solid state lasers has begun.

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Appendix A Status of Gain Saturation Measurements in Nd:doped Silicate, Fluorophosphate and Phosphate Laser Glasses

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We have studied^{A-1,2} saturation of gain in neodymium-doped laser glasses of several compositions: silicates, phosphates, and fluorophosphates. A glass-rod laser amplifier was built with each material. Saturation of gain in these amplifiers was observed during amplification of 1064- or 1053-nm pulses having durations ranging from 1 to 50 ns. For each laser pulse, we measured the amplifier input fluence, E_{in} , the amplifier output fluence, E_{out} , and the small-signal gain G_0 prior to arrival of the pulse. We also measured the end-surface reflectance and passive transmission of laser rods with flat antireflection coated ends, as well as the transmission for rods with Brewster-oriented ends.

A value of saturation fluence, E_s , was computed from the parameters measured during amplification of each laser pulse. Saturation fluences were computed from the Frantz-Nodvik equation^{A-3} which models a homogeneous two-level amplifier. To include absorption losses, we wrote the equation in the form,^{A-4}

$$\ln G_0 = \int_{E_{in}}^{E_{out}} \frac{dE}{E_s [1 - \exp(-E/E_s)] \delta - E/\alpha_0} \quad (A-1)$$

where α_0 is the gain coefficient, and δ is a loss coefficient computed by attributing passive loss to uniform bulk absorption.

The experimental arrangement for our saturation measurements is shown in Fig. A-1. The amplifier test rods were either 2.5 or 4.0 cm in diameter. The active length was 25 cm. The test amplifiers were pumped by six xenon flashlamps connected in series to a circuit with $\approx 90 \mu\text{F}$ and $450 \mu\text{H}$. The flashlamp pulses were about $600 \mu\text{s}$ in duration.

An input beam to the test amplifier was generated by a source laser. Silicate glasses were studied with a 1064-nm input beam generated in a source laser with a Nd:YAG oscillator and

Fig. A-1. Arrangement of saturation experiment. Input and output fluence were measured with calorimeters C1 and C2. The stability of small-signal gain was monitored with a cw 1064-nm beam and photodiodes D1 and D2.

neodymium-doped silicate glass amplifiers. Fluorophosphate and phosphate glasses were tested with a 1053-nm beam from a source laser with a Nd:YLF oscillator and neodymium-doped phosphate glass amplifiers. Pulse duration in the source laser was determined by an electronic shutter, and could be varied without disturbing the optical alignment of the experiment.

To measure E_{in} and E_{out} , calorimeters were placed in diagnostic beams established at the input and exit of the test amplifier. We placed 5-mm-diam apertures in the centers of the diagnostic beams, measured the energy transmitted through the apertures, and computed the spatially averaged fluences in the diagnostic beams as the ratio of the transmitted energy to the area of the aperture. Diagnostic-beam fluences were related to main-beam fluences through the Fresnel coefficients of the bare BK-7 glass splitters from which diagnostic beams were derived. With careful calibration of the absorbing glass calorimeters, spatially-averaged fluence could be measured to within $\pm 1\%$. Over the 5-mm aperture, actual fluence values in the input beam varied locally by 10-30%.

Two techniques were used to measure the small-signal gain G_0 in the central 5-mm-diameter volume of the test amplifier. In measurements (Ref. A-1) of silicates and fluorophosphates, we used the input and output calorimeters to measure the gain for input pulses of very low fluence that produced no observable saturation. In the later study of phosphates (Ref. A-2), the oscillator in the source laser emitted a stable low-level output for 4 ms immediately prior to emission of the Q-switched high power pulse. Photo diodes were used to monitor amplification of this low level signal in the test amplifier, thereby determining G_0 .

In all experiments, we also passed a cw 1064-nm beam diagonally through the test amplifier, and used photodiodes to monitor the intensity of the input beam and the intensity of the amplified output beam (see Fig. A-1). The gain so measured with a diagonal 1064-nm beam was not necessarily the same as the gain G_0 along the rod axis, even in silicate materials when the saturating pulse was at 1064 nm, and gain measured with the 1064 nm beam was never equal to 1053-nm gain in phosphates and fluorophosphates. Therefore, we used the axial measurements of G_0 described above to calibrate the cw 1064-nm gain probe, and then used the cw probe as a measurement of gain stability during subsequent collection of saturation data.

Rod transmission was measured in two-pass or four-pass experiments. The transmission measurements were confirmed, after installation of the rod in the test amplifier, by using the calorimeters to compare input and output fluence for a pulse transmitted through the unpumped amplifier.

A series of experiments (Ref. A-1) was performed to ascertain the accuracy of saturation data. These tests indicated that the spatially averaged fluences E_{in} and E_{out} were measured to within $\pm 1\%$, and that measurements of rod transmission were correct to within $\pm 0.5\%$. The calorimetry used to measure G_0 in silicates and fluorophosphates produced data with random errors as large as $\pm 6\%$, but we believe the gains obtained by averaging several measurements were typically accurate to within $\pm 2\%$. The measurement of G_0 in phosphates was accurate to within $\pm 1\%$.

Figure A-2 shows that the uncertainties in computed values of saturation fluences E_s depend on both experimental uncertainties and the magnitude of the output fluence. The dependence of uncertainty on E_{out} can be understood by noting that the Frantz-Nodvik equation, in essence, allows selection of a value of E_s that accounts for the difference in two values of gain: G_0 , the initial gain and E_{out}/E_{in} , the net saturated gain. When E_{out} is large relative to E_s , the difference in initial and saturated gains is large relative to uncertainties in the measurements, and E_s can be accurately determined. Conversely, the amplification of low fluence pulses produces a gain reduction comparable to measurement uncertainty; and a large uncertainty in computed values of E_s . For currently available measurement accuracies, accurate measurement of E_s cannot be made for $E_{out} \lesssim 0.25 E_s$.

The sensitivity of the Frantz-Nodvik equation to variations in E_{out} , E_{in} , and G_0 does not imply a requirement for extreme spatial uniformity in either the saturating beam or the gain profile of the amplifier. The equation is very insensitive to spatial nonuniformities in both E_{in} and G_0 . For example, the value of E_{out} computed assuming a spatially constant value of G_0 differs by less than 1% from that computed under the assumption that G_0 is the spatial average over a volume exhibiting $\pm 25\%$ gain variations. Therefore, accurate measurements of spatially averaged values of E_{in} , E_{out} , and G_{so} are adequate for determination of E_s .

Fig. A-2. Ratio of uncertainty ΔE_s in computed values of saturation fluence to measurement uncertainty Δm in input fluence as a function of output fluence in a Frantz-Nodvik amplifier with $G_o = 6$ and $E_s = 4$.

An error analysis of the Frantz-Nodvik equation also shows that reasonable estimates of the uncertainty in computed values of E_s are obtained by lumping the total experimental uncertainty and associating the lumped uncertainty with the variable E_{in} . This is particularly true for values of E_s computed for small E_{out} . For silicates and fluorophosphates the maximum probable experimental error is 4.5%, the sum of the four individual measurement uncertainties. For phosphates, the maximum lumped uncertainty is 3.5%. Since it is statistically unlikely that the actual error would equal the linear sum of the four independent errors, we routinely used a lumped uncertainty of 2% in computing uncertainty in E_s .

The glasses that we have tested, their source, and the shape of the amplifier rods tested is given in Table A-1. Table A-2 is a summary of the measurements. The final column of Table A-2 gives, for those glasses where adequate data exists, empirical functions obtained by fitting linear or logarithmic functions to the data.

Table A-1. Test materials for saturation measurements.

Material	Type	Vendor	Rod-size (cm)	End-cuts
ED-2	Silicate	Owens-Illinois, Inc.	4.0×25	Flat, AR-coated
LSG-91H	Silicate	Hoya Corporation	4.0×25	Brewster-cut
OI-H9	Silicate	Owens-Illinois, Inc.	4.0×25	Brewster-cut
LG-56	Silicate	Schott Optical Glass, Inc.	2.5×25	Brewster-cut
E-309	Fluorophosphate	Owens-Illinois, Inc.	2.5×25	Brewster-cut
LG-810	Fluorophosphate	Schott Optical Glass, Inc.	2.5×25	Brewster-cut
LHG-10	Fluorophosphate	Hoya Corporation	2.5×25	Brewster-cut
P101	Phosphate	Hoya Corporation	4.0×25	Brewster-cut
Q-94	Phosphate	Kigre, Inc.	2.5×25	Brewster-cut
LHG-8	Phosphate	Hoya Corporation	4.0×25	Brewster-cut
LG-750	Phosphate	Schott Optical Glass, Inc.	2.5×25	Brewster-cut
Q-88	Phosphate	Kigre, Inc.	2.5×25	Brewster-cut
Q-98	Phosphate	Kigre, Inc.	2.5×25	Brewster-cut
EV-4	Phosphate	Kigre, Inc.	2.5×25	Brewster-cut

Table A-2. Data summary calorimetric measurements of saturation fluence.

Material	Measurement wavelength (nm)	Gain cross section ^a at 1064 nm (cm ²)	Gain cross section ^a at 1053 nm (cm ²)	Rod transmission	Small-signal gain
ED-2	1064	2.6×10^{-20}	—	0.962	6.3
LSG-91H	1064	2.32×10^{-20}	—	0.874	4.1
LG-56	1064	0.81×10^{-20}	—	0.924	4.4
OI-H9	1064	1.45×10^{-20}	—	0.925	3.8
E-309	1053	—	2.44×10^{-20}	0.895	9.5
LG-810	1053	—	2.54×10^{-20}	0.945	6.5
LHG-10	1053	—	2.55×10^{-20}	0.980	7.4
P101	1053	—	3.0×10^{-20}	0.963	6.3
Q-94	1053	—	3.8×10^{-20}	0.982	6.7
LHG-8	1053	—	4.0×10^{-20}	0.974	7.8
LG-750	1053	—	4.0×10^{-20}	0.945	6.9
Q-88	1053	—	4.0×10^{-20}	0.975	7.0
Q-98	1053	—	4.1×10^{-20}	0.992	7.8
EV-4	1053	—	4.2×10^{-20}	0.950	8.0

^a Ref. A-5.

Figures A-3 to A-16 give values of saturation fluence as a function of output fluence, each normalized to the parameter $h\nu/\sigma$, where ν is the laser emission frequency and σ is the cross section for stimulated emission. The output fluence is the fluence immediately inside the exit face of the amplifier rod. For tests with Brewster-cut rods, the fluence external to the rod face was greater by a factor approximately equal to the refractive index of the rod. The term $h\nu/\sigma$ is the predicted saturation fluence for a homogeneous two-level lasing medium in which the lower-level lifetime is short compared to the duration of the saturating pulse.

The data plotted in these figures have several common features. The scatter in values of saturation fluence is large when the output fluence was small relative to $h\nu/\sigma$, and small at large values of E_{out} . Therefore, values of saturation fluence were not accurately determined in those materials which damaged at fluence levels that were low relative to $h\nu/\sigma$, which occurred

Fig. A-3. 1064-nm saturation fluence of ED-2 silicate glass.

**Fig. A-4. 1064-nm
saturation fluence of
LSG-91H silicate glass.**

**Fig. A-5. 1064-nm
saturation fluence of
OI-H9 silicate glass.**

**Fig. A-6. 1064-nm
saturation fluence of
LG-56 silicate glass.**

Fig. A-7. 1053-nm saturation fluence of E-309 fluorophosphate glass.

Fig. A-8. 1053-nm saturation fluence of LG-810 fluorophosphate glass.

Fig. A-9. 1053-nm saturation fluence of LHG-10 fluorophosphate glass.

Fig. A-10. 1053-nm saturation fluence of LHG-8 phosphate glass.

Fig. A-11. 1053-nm saturation fluence of LG-750 phosphate glass.

Fig. A-12. 1053-nm saturation fluence of P101 phosphate glass.

Fig. A-13. 1053-nm saturation fluence of Q-94 phosphate glass.

Fig. A-14. 1053-nm saturation fluence of Q-88 phosphate glass.

Fig. A-15. 1053-nm saturation fluence of Q-98 phosphate glass.

**Fig. A-16. 1053-nm
saturation fluence of
EV-4 phosphate glass.**

in the fluorophosphates and in the silicates LG-56 and OI-H9 for which σ is small. It was also generally observed that E_s increased slowly with E_{out} , a trend that is most clearly established in materials that could be tested at large E_{out} . An increase of E_s with E_{out} is expected (Ref. A-6) due to either spectral or polarization hole-burning, which causes σ to decrease at the test wavelength as energy is extracted from the amplifier.

We also found that values of E_s measured with 1-ns pulses were, in general, slightly below values measured with pulses of longer duration. This suggests that the lifetime of the lower laser level, and of states created through excited state absorption from the upper level, are about 1 ns. This agrees with direct measurements (Ref. A-7) of the lifetimes of states created by exciting neodymium-doped glasses with 1-ns, 532-nm pulses. However, the difference in saturation fluences measured with 1-ns and either 20- or 50-ns pulses is not as large as that predicted by a model (Ref. A-7) that we developed to explain a previously observed large apparent recovery of gain following gain saturation by 1-ns pulses. In those experiments, amplification of a weak probe beam was monitored with 0.5-ns temporal resolution. As expected, the probe beam intensity decreased when the amplifier gain was saturated by a 1-ns pulse, and then increased significantly within a few nanoseconds after passage of the pulse. A theory that was developed to explain this apparent gain increase predicted that saturation fluences measured with pulses 5 ns or longer in duration would be significantly larger than those measured with 1-ns pulses. The weak pulse-duration dependence in data from later experiments discussed here indicate that the model incorporating gain recovery is incorrect. However, time-resolved measurements of gain in a probe beam were made in all current tests of silicates and fluorophosphates, and the apparent post-saturation recovery of gain was always observed. The explanation for the apparent gain recovery is not presently known, but it must be assumed that it is not a simple indication of gain recovery due to relaxation of lower-level population.

Finally, at low output fluences, saturation fluences in silicates and fluorophosphates were systematically lower than saturation fluences in phosphates. Therefore, hole-burning is a less significant effect in phosphates which have narrower and more nearly homogeneous spectral gain profiles (Ref. A-8) than do silicates or fluorophosphates. However, saturation fluence in silicates and fluorophosphates increased with increasing output fluence at a greater rate than did saturation fluences in phosphates. Therefore, we expect less dependence of saturation fluence of glass composition at output fluences $\geq 3 h\nu/\sigma$.

Appendix A References

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Appendix B Extraction Efficiency in Realistic Laser Systems

In principle, the extraction efficiency in a laser material can be made arbitrarily close to unity by increasing the fluence through the material. In practice, the actual extraction efficiency in a system is limited by the damage which occurs at high fluence levels, by the presence of nonsaturable losses in the material or system, by the variation in fluence from input to output, and by the onset of nonlinear propagation effects at high intensity levels. This appendix presents the results of calculations which take these factors into account. Since damage fluence and nonlinear effects depend on laser pulse duration, the results are shown as a function of pulse width.

The damage fluence was assumed to vary according to the equation

$$\phi_D = \phi_0 \sqrt{\tau} \quad (\text{B-1})$$

where τ is the laser pulse width. The nonlinear limit was set by not permitting the B integral to exceed a specified value at the end of a temporally square laser pulse; the results are the same for any pulse having the same energy and a maximum power which is reached at the end of the pulse. All calculations assumed the gain was in slabs at Brewster's angle, and that the losses were uniformly distributed through the material.

Figure B-1 repeats Fig. 21 from the main text, and shows the effect of varying small signal gain. Dots on the curves indicate the transition from nonlinear limitations (short pulse) to fluence limitations (long pulse). Figure B-2 shows how changes in the nonsaturating loss coefficient γ affect the extraction. Figures B-3 to B-5 illustrate the effect of changes in the stored energy density (pumping level), damage limit at 1 ns, and nonlinear or ΔB level. Finally, Fig. B-6 demonstrates how changing the type of glass used (low, moderate, or high cross section) changes the extraction efficiency. Note that changing the glass type may also affect the inversion density, nonlinear index, and fixed loss coefficient; these parameters were not changed in Fig. B-6.

Fig. B-1. Extraction efficiency as a function of pulse width for laser amplifiers with various values of the small signal gain G . On any one curve, the nonlinear limit (ΔB) applies to the left of the dot, and the fluence limit to the right of the dot.

Fig. B-2. Extraction efficiency as a function of pulse width for laser amplifiers with various values of the fixed loss coefficient γ .

Fig. B-3. Extraction efficiency as a function of pulse width for laser amplifiers with various values of the stored energy density E_s .

Fig. B-4. Extraction efficiency as a function of pulse width for laser amplifiers with various values of the damage fluence at 1 ns (damage varies as $\sqrt{\tau}$).

Fig. B-5. Extraction efficiency as a function of pulse width for laser amplifiers with various values of the maximum allowed added B integral ΔB .

Fig. B-6. Extraction efficiency as a function of pulse width for laser amplifiers with various values of the cross section σ .

Appendix C Impact of Cooling on System Efficiency

The vast majority of solid state laser media utilized today operate at ambient temperature or above. A large number of impurity-doped solid state media which might perform well as laser media at cryogenic temperatures often cannot be used at higher temperatures for two basic reasons: (1) excessive thermally-induced quenching of the upper laser level, and (2) operation as a "three-level" system with a degraded extraction efficiency (relative to a "four-level" laser with its thermally-empty terminal level). Since the number and kinds of potentially useful solid state gain media increase drastically once the notion of operation at a cryogenic temperature is admitted, we need to establish the technical and economic circumstances under which cryogenic cooling would be acceptable in a given application.

As a first step in assessing circumstances under which cryogenic cooling is permissible, a simple calculation is presented (Ref. C-1) which gives the overall system efficiency of a laser with a given "electrical" efficiency, as a function of operating temperature. Calculations are made for systems cooled with "ideal" Carnot refrigerators and for systems cooled with "real" refrigerators as experienced in the cryogenics industry (Ref. C-2).

Consider a solid state laser system with an electrical efficiency, η_{el} , defined as the ratio of the laser output energy, E_{out} , and the input electrical energy, E_{pump} , required to pump the gain medium

$$\eta_{el} \equiv E_{out}/E_{pump} \quad (C-1)$$

Let the system efficiency, η_{sys} , be defined as the ratio of the laser output energy and the total energy input required to pump and cool the laser medium, $E_{pump} + E_{cool}$

$$\eta_{sys} = \frac{E_{out}}{E_{pump} + E_{cool}} \quad (C-2)$$

Next, we express the output energy as a fraction, η_{ext} , of the stored energy, E_{stor} , and express the heat energy deposited in the gain medium, E_{heat} , as a factor χ times the stored energy

$$E_{out} = \eta_{ext} E_{stor} \quad (C-3)$$

$$E_{heat} = \chi E_{stor} \quad (C-4)$$

The latter is a useful parameterization, since the specific thermal load, $\chi = E_{heat}/E_{stor}$, tends to be a constant independent of the degree of pumping and the temperature (for a given type of laser—see below). Using these relationships, we can express the system efficiency as

$$\eta_{sys} = \frac{\eta_{el}}{1 + \left(\frac{\chi \eta_{el}}{\eta_{ext}} \cdot \frac{E_{cool}}{E_{heat}} \right)} \quad (C-5)$$

We now need to find the temperature dependence of the quantity (E_{cool}/E_{heat}) appearing in Eq. (C-5). First, consider cooling performed with an "ideal" Carnot refrigerator. The Second Law of Thermodynamics requires that a minimum energy, E_{cool} , is required to remove an

amount of heat energy, E_{heat} , from a body at cold temperature, T_c , and reject it at a higher temperature, T_a . The ratio of these two energies, which we will refer to as the cooling energy ratio, is given by

$$\frac{E_{\text{cool}}}{E_{\text{heat}}}\bigg|_{\text{min}} = \left(\frac{T_a - T_c}{T_c} \right) \quad (\text{C-6})$$

This expression is plotted in Fig. C-1 for a rejection temperature $T_a = 300$ K. The cooling energy ratio is less than 0.1 for cold temperatures above 270 K (providing the basis for the "heat pump") and is still less than unity for cold temperatures above 150 K. For lower temperatures this ratio begins to soar, approaching infinity at absolute zero temperature.

Of course, the ideal Carnot refrigerator cannot be achieved in practice. Industrial experience (Ref. C-2) gained in the commercial production of large volumes of cryogenic liquids suggests that the cooling energy ratio of a real refrigerator at a given temperature T_c is larger than that of an ideal refrigerator by a factor proportional to the ideal energy ratio, Eq. (C-6). To a good approximation, the cooling energy ratio of real refrigerators (Ref. C-2) can be expressed as

$$\frac{E_{\text{cool}}}{E_{\text{heat}}} = 2.5 \left(\frac{T_a - T_c}{T_c} \right)^{4/3} \quad (\text{C-7})$$

This expression also has been plotted in Fig. C-1 to facilitate a comparison of real and ideal refrigerators as a function of temperature. Refrigerator performance degrades rapidly from the ideal with decreasing temperature. (Note, however, that it may be possible to significantly improve on the performance of current real refrigerators with additional engineering development of compressors, heat exchangers, transfer tubing, etc.) Cost estimates for refrigerator equipment suitable for operation in the various cryogenic temperature regimes have not yet been made, but it is anticipated that capital costs will scale rapidly upward as the temperature is lowered because the temperature gradient is increasing and because more cooling capacity is required per unit of heat removed.

Fig. C-1. Normalized energy required to cool a medium from temperature $T_{\text{ambient}} = 300$ K to cold temperature T_c using an ideal Carnot cycle or a real refrigerator.

Using the information contained in Equation (C-7), we can estimate laser system efficiency including cryogenic cooling

$$\eta_{\text{sys}} = \frac{\eta_{\text{el}}}{1 + \left(\frac{2.5 \chi \eta_{\text{el}}}{\eta_{\text{ext}}} \cdot \left[\frac{T_a - T_c}{T_c} \right]^{4/3} \right)} \quad (\text{C-8})$$

It is useful for purposes of illustration to evaluate this equation for three basic types of solid state lasers, each with a distinct characteristic value of the specific thermal heating factor, χ . These basic laser types are illustrated in Fig. C-2. The Type 1 laser, shown in Fig. C-2(a), is typified by the Nd:glass laser in which the upper laser level is excited via absorption of broadband pump energy in higher-lying energy levels, followed by multiphonon relaxation and lattice heating. Significant concentration quenching of the upper laser level may also occur and the pump-pulse duration is assumed to be comparable to the fluorescence lifetime. In many respects, a second example of this type of laser is the chromium sensitized Yb:glass laser. For such lasers pumped with broad-band flashlamps, the heat energy deposited is typically twice the stored energy, so $\chi = 2$.

The Type 2 laser, illustrated in Fig. C-2(b), is typified by a semiconductor-diode-pumped Nd:crystal laser. It utilizes narrow band pumping in a pump band lying only slightly above the

Fig. C-2. Electronic energy-level schemes for energy-storage solid state lasers and associated values for specific thermal loading, $\chi = E_{\text{heat}}/E_{\text{store}}$.
a) broadband flashlamp pump, $\chi = 2$, b) narrowband, non-resonant pumped, $\chi = 0.4$; c) narrowband, resonant pump, $\chi = 0.2$.

upper laser level so that the energy defect is relatively small. Following stimulated emission, the terminal laser level relaxes back to the ground level with additional lattice heating. Here it is envisioned that concentration quenching is negligible and that the pump-pulse duration is short compared with the fluorescence lifetime. For this case, a value of $\chi = 0.4$ is appropriate.

The Type 3 laser, illustrated in Fig. C-3(c), is typified by a Yb:crystal laser resonantly pumped by semiconductor diode lasers. Here, lattice heating occurs only as a result of relaxation of Stark levels within a J-manifold; energy defects are absolutely minimal, and ion-ion quenching is completely absent. For this case a value of $\chi = 0.2$ is appropriate.

To get a feel for how cryogenic cooling impacts the system efficiency of these types of lasers, let us assume that the electrical efficiency of each is 15% at any temperature of operation we wish to consider. Let us also assume that the extraction efficiency is 0.5, a conservative value taking into account typical fill-factors, nonsaturable losses, degeneracy ratios, etc. Figure C-3 plots the system efficiency of each type of laser as a function of the operating temperature. If we require system efficiency to be at least 10%, then the various types of lasers with electrical efficiencies of 15% could not be operated at cold temperatures lower than the following values: Type 1 (210 K), Type 2 (120 K), and Type 3 (85 K). Figures C-4 and C-7 show plots for the minimum cold temperature as a function of laser electrical efficiency for the three characteristic values of specific thermal loading, $\chi = 0.2, 0.4$, and 2.0 . The system efficiencies are set equal to 8, 10, 15, 20% in Figs. C-4 to C-7, respectively. Once the specific thermal loading, χ , and the electrical efficiency of a laser medium are known, these figures can be used to estimate the maximum system efficiency attainable upon inclusion of cryogenic cooling of the medium.

Fig. C-3. Total laser system efficiency as a function of cold temperature for laser media with 15% electrical efficiencies and χ values of 2, 0.4, and 0.7.

Fig. C-4. Minimum cold temperature as a function of medium electrical efficiency which maintains the total laser system efficiency greater than 8%. Specific thermal load χ is a parameter.

Fig. C-5. Minimum cold temperature as a function of medium electrical efficiency which maintains the total laser system efficiency greater than 10%. Specific thermal load χ is a parameter.

Fig. C-6. Minimum cold temperature as a function of medium electrical efficiency which maintains the total laser system efficiency greater than 15%. Specific thermal load χ is a parameter.

Fig. C-7. Minimum cold temperature as a function of medium electrical efficiency which maintains the total laser system efficiency greater than 20%. Specific thermal load χ is a parameter.

Appendix C References

- C-1. W. F. Krupke, *Cryogenic Cooling of Solid State Laser Gain Media*, Lawrence Livermore National Laboratory, Livermore, Calif., Internal Memorandum, WFK 82-127, July 27, 1982.
- C-2. *Applied Cryogenic Engineering*, University of California Engineering and Physical Sciences Extension Series, New York, R. W. Vance and W. M. Duke, Editors (John Wiley & Sons, New York), p. 171.